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Uncertainty Analysis of Zone Fire Models

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ABSTRACT

Zone fire models are used by practising engineers every day in New Zealand, yet the models have limitations, and the uncertainty of these models has not been well documented. Comparisons with experimental data are simply comparison and do not analyse the uncertainty of the models, nor are they validation of the models.

The object of this research has been to discuss the uncertainties in components of zone models and show how uncertainty within user supplied data affects the results obtained.

The zone fire model selected for analysis is the second version of CFAST. A numerical uncertainty analysis is performed, utilising sensitivity factors as the basis of the analysis. In the analysis, no assumptions are made as to the independency of the input variables. A large amount of information is appended, with a discussion of pertinent results.

Several input variables were identified to resulted in discernible uncertainty in the output. Consisting of the heat release rate, radiative fraction, ambient temperature, ambient pressure, and ceiling height.

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NOMENCLATURE

Symbols

A	area [m^2]
c_p	heat capacity at constant pressure [J/kg K]
c_v	heat capacity at constant volume [J/kg K]
C_p^{ig}	heat capacity in the ideal-gas state, constant pressure [J/kg K]
g	gravitational constant
h	height of opening [m]
$\dot{h}_L$	rate of addition of enthalpy into the lower layer [W]
$\dot{h}_U$	rate of addition of enthalpy into the upper layer [W]
H	height of the room above the fire [m]
i	equals L for lower layer, U for the upper layer
L_c	characteristic length, taken to be the height of the room
$\dot{m}$	mass loss rate [kg/s]
$\dot{m}_{flux}$	mass loss flux [kg/m^2s]
$\dot{m}_{fuel}$	pyrolysis rate [kg/s]
$\dot{m}_e$	mass entrainment rate [kg/s]
m_i	total mass in layer i [kg]
$\dot{m}_L$	mass flow rate into the lower layer [kg/s]
$\dot{m}_U$	mass flow rate into the upper layer [kg/s]
$\dot{m}_{13}$	mass flow rate between two adjoining upper layers [kg/s]
P	input perturbation
P	Pressure [Pa]
P_{ref}	reference pressure [Pa]
$\dot{q}$	dimensionless heat release rate

$\dot{Q}$	heat release rate [kW]
$\dot{Q}_o$	characteristic heat release rate for ASET
$\dot{Q}_{eq}$	equivalent plume heat release rate [kW]
$\dot{Q}_{vent}$	ventilation limit [kW]
R	universal gas constant [J/kg K]
SF	sensitivity factor
t	time
t_{act}	time when sprinkler operates
t_{rate}	constant relating sprinkler spray density
t_c	characteristic time for ASET
T	temperature [K]
T_a	ambient temperature [K]
T_L	upper layer temperature [K]
T_U	upper layer temperature [K]
U	output uncertainty
V	volume [m³]
V_L	lower layer volume [m³]
V_U	upper layer volume [m³]
x	input variable
x^*	basecase value
x'	perturbed variable
X	continuous random variable
y	output variable
y^*	basecase value
y'	perturbed variable
Y	continuous random variable
Z	plume height above virtual origin [m]
Z_i	elevation of layer interface [m]

$f_X(x)$	probability density function
$f_Y(y)$	probability density function

Greek symbols

δ	dimensionless height of fire above the floor
Δ	height of fire above the floor
ΔH_c	heat of combustion [kJ/kg]
ΔP	pressure difference [Pa]
ϕ	dimensionless upper layer temperature
γ	ratio of c_p to c_v
λ_{conv}	convective heat loss fraction (plume)
λ_{cond}	convective heat loss fraction (overall)
λ_{rad}	radiative heat loss fraction (plume)
ρ	gas density [kg/m³]
ρ_a	ambient gas density [kg/m³]
ρ_L	lower layer gas density [kg/m³]
ρ_U	upper layer gas density [kg/m³]
τ	dimensionless time
ζ	dimensionless layer interface height

Chapter 1 : INTRODUCTION

Zone fire models are regularly used in conjunction with an egress model to predict the performance of a fire engineered solution. Zone models in common use in New Zealand today include CFAST, FASTLite, FPEtool, and FireClac. A numerical uncertainty analysis is performed, utilising sensitivity factors as the basis of the analysis. The objective being to make fire engineers aware of the degree of uncertainty involved within the results obtained from zone fire models. Specifically, those of prime interest being the variables related to identifying the onset of life threatening conditions.

Another area of interest is identified here, and that is the uncertainty incorporated within egress models. These models however, are complicated by the fact that human behaviour can be an overriding element. Human behaviour and response are accounted for by adding to the evacuation time. The total time required for egress, is then doubled to give the Required Safe Egress Time, which then must be less than the Available Safe Egress Time, Buchanan 1995. These considerations effectively reduce the effects of any uncertainties incorporated or introduced into the model.

Due to the vast number of simulations required by a numerical analysis and the subsequent analysis itself, it has been decided to focus on one particular zone fire model. The zone fire model selected for analysis is the second version of CFAST. The selection was based on several influencing factors, those being: the model's popularity in use, the allowance for multicompartment configurations, the wide range of input variables that can be altered, and the amount of data generated for analysis.

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) are currently working on a new version of CFAST. This new version, CFAST 3.0, is currently at the beta release testing stage. It was initially intended to use the beat release of CFAST 3.0 as the basis for analysis. However, since it is only a beta version, the code is currently in a state of flux. Thus, any analysis on the beta version may prove to be incompatible with that of the final release. However, as a point of interest, the two models are briefly compared to one another.

An explanation of the zone model approximation and the basis of the assumptions applied to simplify the physical situation appears in Chapter 2. A discussion of the governing equations and correlations used within the models selected, including the mathematical basis of the zone model.

The limitations of CFAST 2.0 comprises areas such as the idea of homogeneous zones (uniform temperature, density, and species concentration), vent flow mixing, and the range of validity for the correlations used.

Chapter 2 : ZONE MODELS

There are several types of fire models, network models, field models, and zone models or finite element models. Network models have one element per room, and are used to predict conditions in rooms far from the fire room, where temperatures are closer to ambient and layering is assumed not to have occurred. Field models take the opposite approach, in that the fire room and any adjoining spaces can be divided up into as many elements as desired. Zone fire models constitute a compromise between network and field models.

Zone fire models have been based on an observation from full scale compartment fire tests that a stratification occurs, forming a buoyant hot gas upper layer, and a cooler lower layer as presented in Figure 2-1.

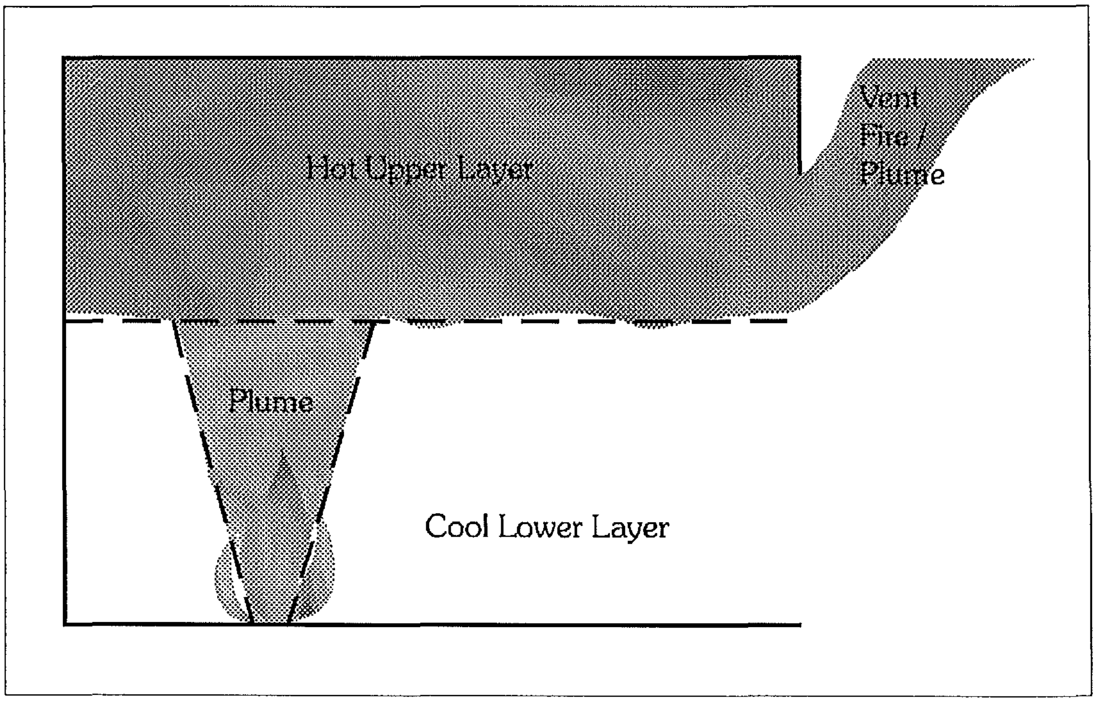


Figure 2-1 Zone Model Approximation

In CFAST, the plume is a third zone in the fire room, whereas all other rooms have two zones. Zone fire models have the advantage over field models in that they are less expensive to purchase, do not require expensive hardware, and require shorter run times.

The zones are considered to be internally homogeneous, that is they have a uniform temperature and species concentration, whereas field models can predict variations within layers. The zone fire model approximation in itself leads to an inherent discrepancy with reality.

CFAST solves a set of differential equations that predict state variables such as temperature, pressure, and volume. The equations are based on enthalpy and mass flux as a function of time. The set of equations are derived from the conservation equations of mass and energy, utilising definitions for density and internal energy, and the ideal gas law. The conservation equations must always be correct; any errors made by the model arise from the simplifying assumptions, processes left out, or from empirical approximations.

CFAST 3.0 β

New subroutines included in the model are detection, suppression, specific heat flux to a target, heat transfer through boundaries by conduction, and flame spread.

Cedit, forming an integral part of the CFAST 3.0 suite, has had the Graphical User Interface (GUI) ported over from FASTLite, with the salient difference that the model can not be run interactively from the desktop, (even though the option is included in the menu). As in FASTLite, each of the buttons brings up a window where the relevant data is entered. Initially when creating a new scenario, the number of rooms, along with the fire growth rate can be selected. The option is available to select a heat release rate from a database compiled from experimental results.

The specific heat flux to a target is used in the flame spread model for ignition. The Quintiere-Cleary model for flame spread is used, Quintiere 1993, and is based on five differential equations, on each for concurrent, and opposed flow flame spread, the two burn out fronts, and the last for burn out at the ignition point. The flame spread model describes the growth of a rectangle.

Detection is based on the ceiling jet temperature where they exist, and on the gas layer temperature elsewhere, Jones 1996. Smoke detectors are activated using a thermal analogy, Jones 1996.

The sprinkler fire suppression is based on a simple zero'th order model, Evans 1993, of the form:

$$e^{-(t-t_{act})/t_{rate}}$$

where

t_{act}	time when sprinkler operates
t_{rate}	constant relating sprinkler spray density

Jones 1996, makes the comment that the model does not allow for the possibility that the fire may overpower the sprinkler, nor for the effect of a second sprinkler operating and further suppressing the fire.

CFAST 2.0

The conservation equations for mass and energy are subsidised by the ideal gas law and definitions for density and internal energy to yield the following selected set of five equations:

$$P = P_{ref} + \Delta P \tag{1}$$

where

P	Pressure [Pa]
P_{ref}	reference pressure [Pa]
ΔP	pressure difference [Pa]

$$\frac{dP}{dt} = \frac{\gamma - 1}{V}\left(\dot{h}_L + \dot{h}_U\right) \tag{2}$$

where

γ	ratio of c_p to c_v
c_p	heat capacity at constant pressure [J/kg K]
c_v	heat capacity at constant volume [J/kg K]
V	volume [m^3]
$\dot{h}_L$	rate of addition of enthalpy into the lower layer [W]
$\dot{h}_U$	rate of addition of enthalpy into the upper layer [W]

$$\frac{dV_U}{dt} = \frac{1}{\gamma P}\left((\gamma - 1)\dot{h}_U - V_U\frac{dP}{dt}\right) \tag{3}$$

where

V_U upper layer volume [m³]

$$\frac{dT_U}{dt} = \frac{1}{c_p \rho_U V_U} \left(\left(\dot{h}_U - c_p \dot{m}_U T_U \right) + V_U \frac{dP}{dt} \right) \tag{4}$$

$$\frac{dT_L}{dt} = \frac{1}{c_p \rho_L V_L} \left(\left(\dot{h}_L - c_p m_L T_L \right) + V_L \frac{dP}{dt} \right) \tag{5}$$

where

T_L	upper layer temperature [K]
T_U	upper layer temperature [K]
ρ_L	lower layer gas density [kg/m³]
ρ_U	upper layer gas density [kg/m³]
V_U	upper layer volume [m³]
$\dot{m}_L$	mass flow rate into the lower layer [kg/s]
$\dot{m}_U$	mass flow rate into the upper layer [kg/s]

The ideal gas law appears in the form:

$$P = R \rho_i T_i$$

where

R	universal gas constant [J/kg K]
i	equals L for lower layer, U for the upper layer

Density is expressed as:

$$\rho_i = \frac{m_i}{V_i}$$

Internal energy is defined as:

$$E_i = c_v m_i T_i$$

where

E_i internal energy in layer i [W]

APPROXIMATIONS IN CFAST 2.0

The dependence on pressure in all of the differential equations can be seen from the equation set. It should also be noted that the use of the ideal gas law in itself leads to discrepancies from reality at low temperatures or high pressures. This is due to the fact that it is derived with the assumptions that the pressure of the system is zero and there are no molecule to molecule interactions. Most pure gases obey the ideal gas law, but in reality deviations from ideal behaviour can be detected at ambient temperatures for most gasses and vapours, becoming less obvious at elevated temperatures.

The use of cubic equations of state such as van der Waals, Redlich / Kwong, or a generalised correlation would minimise these discrepancies, yet at the same time are not too complex as to be inhibitive.

The universal gas constant, R, the specific heat at constant pressure, c_p, the specific heat at constant volume, c_v, and the ratio of the specific heats, γ, are related by $\gamma = c_p / c_v$ and $R = c_p - c_v$. In the model the values of $c_p \approx 1000$ kJ/kg K (≈ 34.5 J/mol K) and $\gamma = 1.4$ are used.

The assumption that γ is constant for an ideal gas is equivalent to the assumption that the specific heat capacities are constant. However, since both c_p and c_v increase with temperature, this is not quite the case.

The value of 1.4 used for the ratio of specific heats is for diatomic molecules, while for simple polyatomic molecules such as CO_2 and H_2O, $\gamma = 1.3$.

By inspection of Table 2.1 and Table 2.2 it can be seen that the use of a single value for the specific heat of the compartment gasses can introduce errors in the results. The two tables present the differences associated with the use of the ideal gas law.

	c_p [J/mol K]				
Temperature [K]	298	500	1000	1500	2000
Species					
CO	29.14	29.79	33.18	35.22	36.25
CO_2	37.129	44.626	54.308	58.379	60.350
H_2O (g)	33.577	35.208	41.217	46.999	51.103
N_2	29.125	29.577	32.698	34.852	35.987
O_2	29.372	31.091	34.878	36.560	37.777

Table 2.1 Heat Capacities of Selected Gases at Constant Pressure

The values presented in Table 2.1 are taken from Drysdale 1995, table 1-5.2 of the SFPE Handbook, while those in Table 2.2 are derived from an empirical correlation values supplied in table 4.1, Smith 1987.

	C_p^{ig} [J/mol K]				
Temperature [K]	298	500	1000	1500	2000
Species					
AIR	29.168	30.231	32.661	35.058	37.451
CO	29.158	30.280	32.673	35.003	37.323
CO_2	37.127	45.866	53.096	57.974	62.505
H_2O (g)	33.575	35.280	41.005	46.977	52.985
N_2	29.114	29.868	32.233	34.680	37.139
O_2	29.383	31.603	34.273	36.481	38.621

Table 2.2 Heat Capacities of Selected Gases in the Ideal-Gas State

By specifying a value of c_p greater than that found at room temperature, CFAST will initially under predict the temperature according to the following relationship:

$$\dot{Q} = \dot{m}\, c_p\, \Delta T$$

where

$\dot{Q}$ heat release rate [kW]

$\dot{m}$ mass loss rate [kg/s]

ΔT temperature difference [K]

Put simply, the heat release rate is the amount of energy that is transported into the upper layer, and the mass loss rate applies to the total amount of mass in the upper layer. By over specifying the specific heat capacity of the upper layer gaseous species, for a given heat release rate and mass loss rate, the resulting temperature rise will be smaller than expected. Directly connected to this by the ideal gas law is the density for the resulting upper layer. The lower temperature will result in a higher density, and hence a higher interface layer height. Both of these variables are very important in the determination of untenable conditions. With the outcome that both of these effects would predict the onset of untenable conditions at a later time than might be expected.

Brani *et al* 1992 produced a single room zone model to investigate the effects of several simplifying assumptions within zone fire models. Of interest here is the assumption ignoring how temperature affects the specific heat capacity of the gaseous species in the fire compartment. Their findings are supportive of the hypothesis derived above, with the interesting accretion. The zone fire model had the ability to determine the specific heat capacity of the gaseous mixture of species within the compartment dependent upon the temperature that they were at.

The results produced were then compared to two different scenarios of constant specific heat capacity with temperature. The first used a constant value based on the initial conditions in the compartment, set at 27 °C and referred to as constant initial. The second utilised two values based on the lower layer of 27 °C and the hot upper layer of 427 °C, and is referred to as constant average.

It was found that the constant initial value slightly over predicted the smoke temperature rise when compared to the variable results, but the constant average value under predicted the smoke temperature rise, generally lagging by 40 seconds. Similar results are found for both the interface layer height and the mass flow out of the compartment.

Thus, when life safety is being considered, the use of a constant high value for the specific heat capacity of 1000 kJ/kg K (corresponding to a temperature of approximately 1500 [K]) in CFAST is quite unconservative.

Heat Release Rate

The heat release rate in CFAST is based on the data entered into the model by the user. This in itself creates a limitation of the model, that is the possibility for heinous misuse. The use of the t^2 fire has become a widely accepted means of practice, with the belief that such fires can be used to approximate reality. It should be acknowledged that the t^2 fire evolved as a quantitative basis for analysis of fire detectors, Babrauskas 1996, as it was useful to categorise heat release rates into groups. Thus four t^2 growth rates were defined by the time required to reach a heat release rate of 1000 [kW]. These were defined as 75 seconds for an ultrafast fire, 150 for fast, 300 for medium, and 600 seconds for a slow fire.

Plume Correlation

The mass of air that is entrained into the plume has a direct influence on the temperature and volume of the upper layer. Thus the selection of the plume entrainment submodel is very important, along with an inclusion of the range of validity for the model. The work of McCaffrey 1983 is used to estimate the mass entrainment rate, and is based on a point source approximation. The flaming region and the plume are divided into three regions of differing behaviour:

$$\text{flaming:} \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.011\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{0.566} \qquad 0.00 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right) < 0.08$$

$$\text{intermediate:} \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.026\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{0.909} \qquad 0.08 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right) < 0.20$$

$$\text{plume:} \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.124\left(\frac{Z}{\dot{Q}^{2/5}}\right)^{1.895} \qquad 0.20 \le \left(\frac{Z}{\dot{Q}^{2/5}}\right)$$

where

$\dot{m}_e$ mass entrainment rate [kg/s]

$\dot{Q}$ heat release rate [kW]

Z plume height above virtual origin [m]

In the original paper that these correlations are taken from, McCaffrey 1983, the experiments were base on heat release rates ranging from 14.4 to 57.5 [kW].

Vent Flow Mixing Approximation

The use of an approximation for vent flow mixing based on an equivalent plume also introduces discrepancies with reality. An equivalent plume is created, modified for the rectangular geometry of vents, which is then used to solve the empirically derived entrainment equation. This is done by determining an equivalent plume heat release rate from the mass flow between the two upper layers in adjoining compartments as shown in Figure 2-2, overleaf.

The temperatures used are for the upper layer of the first compartment and the lower layer of the second compartment, to give the following relationship:

$$\dot{Q}_{eq} = \dot{m}_{13}\, c_p \left(T_1 - T_4\right)$$

where

$\dot{Q}_{eq}$ equivalent plume heat release rate [kW]

$\dot{m}_{13}$ mass flow rate between two adjoining upper layers [kg/s]

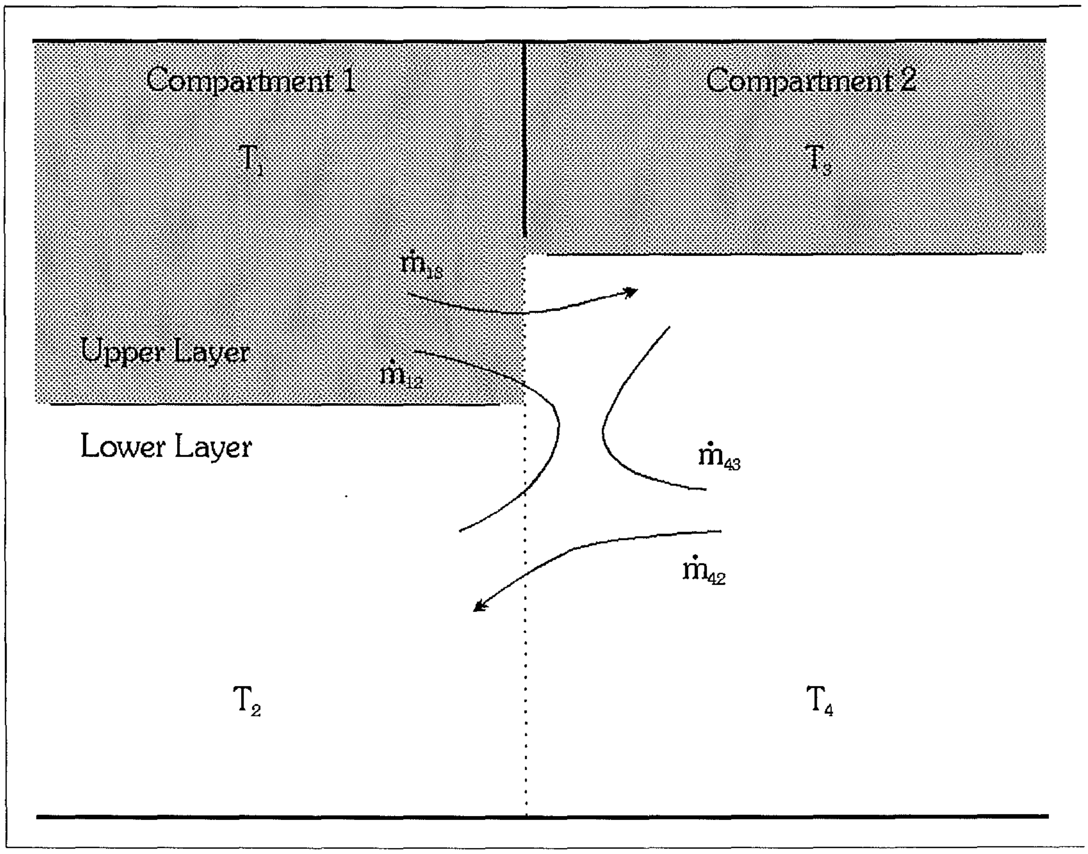


Figure 2-2 Schematic of Vent Flows

Here again, it becomes evident the importance of the use of a value for the specific heat capacity. This value is then used to determine the virtual source point and the height of the plume, from which the entrainment is determined.

The coefficients used in the entrainment correlations are empirically derived values. Any uncertainty in these coefficients will appear in the plume and vent flows. The uncertainty propagates through each vent, which could result in quite large discrepancies at rooms distant from the fire room.

In the real physical situation, the entrainment arises from a phenomenon called the Kelvin-Helmholz instability, Jones 1993. Thus a discrepancy is created when this entrainment is approximated by a normal plume entrainment correlation. No allowance is made for the effect of the interaction of several plumes, nor for the effect of the incoming air on a plume positioned beside a doorway, both of which can create turbulence that will enhance the rate of mass entrainment into the plumes.

Fuel Oxygen Mass Fraction

The use of the facility in Cedit to provide information on the oxygen mass fraction of the fuel has been observed to introduce errors in the results obtained. This is due to the fact that the oxygen parameter does not work, Jones 1997. It has been observed that an initial increase in the concentration of oxygen in both layers arises when a fuel oxygen mass fraction is specified. The same behaviour has been observed in the beta release of CFAST 3.0.

Lower Oxygen Limit

In a similar vein to the fuel oxygen mass fraction is the lower oxygen limit. It has been observed that the value specified has no effect on the occurrence of a vent fire. This however, is not such a detrimental bug in the program. The problem with specifying one value for the lower oxygen limit, is that it actually changes with temperature. Thus, as long as the vent fire is not present when the oxygen concentration is such that combustion would not occur at that temperature, no extraneous errors are introduced.

Energy Balance

The observance of an initial decrease in the lower layer temperature indicates that there is a bug in the program relating to the energy balance.

Material Thermal Properties

An error is introduced by the assumption that the effect of the changing thermal properties of a material with temperature is small. It is noted that while it would be quite simple to add this information to the computer code, Jones *et al* 1993, make the observation that data is scarce over a broad range of temperatures, even for the most common materials.

Carbon Monoxide Yield

Bench scale carbon monoxide production data is generally used due to the lack of full scale data available. Babrauskas 1995 makes the comment that the production of carbon monoxide is the single most important factor leading to death in fires, in the United States, deaths are mainly associated with fires that have gone to flashover.

The transient nature of the fire growth must be accommodated, with the production of carbon monoxide depending on several factors. Initially the fuel properties dictate the production of carbon monoxide, and are similar to those seen in small scale tests. Then the equivalence ratio comes to bear, which is defined as:

$$\varphi = \frac{(\text{kg fuel/kg air})}{(\text{kg fuel/kg air})_{\text{stoichiometric}}}$$

With an increasing equivalence ratio comes an increasing production of carbon monoxide, up to a constant value of 0.2 [kg CO / kg fuel] once flashover is reached. Effectively, this would require the model to be run to determine the fire behaviour, and once again to determine the production of carbon monoxide.

Chapter 3 : UNCERTAINTY ANALYSIS

ANALYTICAL ANALYSIS

For simple models, such as ASET, analytical techniques can be readily applied. ASET is a single room model that predicts the interface height and the average upper layer temperature. The equations that model ASET-B, a Basic version of the FORTRAN program written by Cooper and Stroup, are defined in terms of a dimensionless time, upper layer temperature, layer interface position, and heat release rate, as follows:

$$\frac{d\zeta}{d\tau} = f_1\left(\zeta, \phi, c_1, c_2, \tau\right) = \begin{cases} -c_1\dot{q} - c_2\dot{q}^{1/3}\,\zeta^{5/3}, & 0<\zeta\le\zeta_0 \\ -c_1\dot{q}, & -\delta<\zeta\le 0 \\ 0, & \zeta<-\delta \end{cases}$$

$$\frac{d\phi}{d\tau} = f_2\left(\zeta, \phi, c_1, c_2, \tau\right) = \begin{cases} \dfrac{\phi\left(c_1\dot{q} - (\phi - 1)c_2\dot{q}^{1/3}\,\zeta^{5/3}\right)}{\zeta_0 - \zeta}, & 0<\zeta<\zeta_0 \\ \dfrac{\phi\, c_1\dot{q}}{\zeta_0 - \zeta}, & -\delta\le\zeta\le 0 \end{cases}$$

where the dimensionless variables are defined as $\zeta = Z_i/L_c$, $\tau = t/t_c$, $\phi = T/T_a$, and $\dot{q} = \dot{Q} / \dot{Q}_0$, and where:

ζ	dimensionless layer interface height
τ	dimensionless time
$\dot{q}$	dimensionless heat release rate
δ	dimensionless height of fire above the floor
ϕ	dimensionless upper layer temperature

The constants c_1 and c_2 are defined as:

$$c_1 = \frac{(1 - \lambda_{cond})\,\dot{Q}_0\, t_c}{A\, L_c\, \rho_a\, c_p\, T_a}$$

where

λ_{cond}	conductive heat loss fraction
$\dot{Q}_o$	characteristic heat release rate
t_c	characteristic time
A	area [m^2]
L_c	characteristic length, taken to be the height of the room
ρ_a	ambient gas density [kg/m^3]
T_a	ambient temperature [K]

$$c_2 = \frac{0.210\, t_c}{A} \left(\frac{(1 - \lambda_{rad})\,\dot{Q}_0\, g\, L_c^2}{\rho_a\, c_p\, T_a} \right)^{1/3}$$

where

g	gravitational constant
λ_{rad}	radiative heat loss fraction

The two equations for upper layer temperature and layer interface position are put in discrete form and differentiated with respect to room surface area putting the final sensitivity equation in finite difference form. This can be incorporated into the program and solved for along with the equations for upper layer temperature and layer interface position. The reader is directed to Peacock *et al* for a detailed analysis.

NUMERICAL ANALYSIS

For more complex models these techniques become increasingly difficult. Thus an estimation of uncertainty in model predictions could be found using a numerical approach.

Sensitivity and Uncertainty

A series of sensitivity factors will be used to obtain an idea of the uncertainty involved within the model. This idea is explained with the help of Figure 3-1 presented below.

In Figure 3-1, $f_X(x)$ and $f_Y(y)$ are the probability density functions for the input and output variables respectively.

Values of y are found from the function relating y to x:

$$y = g(x),$$

the symbol g is used here to avoid confusion between algebraic functions and probability density functions.

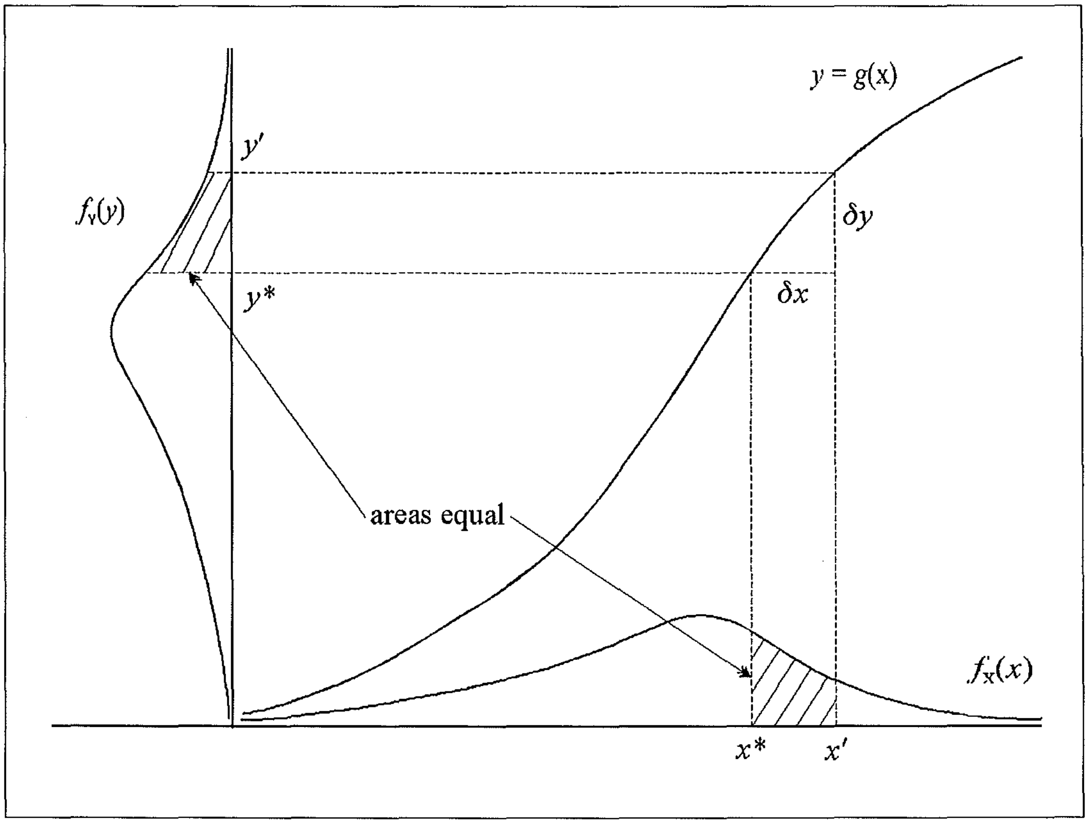


Figure 3-1 Relationship Between Sensitivity and Uncertainty

Sensitivity

If a given input variable, say x^*, is taken as the basecase, and x' is taken as the perturbed variable, resulting in the output variables y^*, the basecase, and y' the perturbed output variable.

The sensitivity of the output to perturbations in the basecase can be summarised by the idea of sensitivity factors. Sensitivity factors are defined as:

$$\mathrm{SF} = \frac{(y' - y^*)/y^*}{(x' - x^*)/x^*}$$

This can be described as the ratio of the percentage change in the outputs to the percentage change of the inputs. Alternatively by setting $y' - y^* = \delta y$:

$$\mathrm{SF} = \frac{\delta y}{\delta x}\frac{x^*}{y^*}$$

Thus sensitivity factors obviously give the sensitivity of the output variables to changes in the input variables.

Uncertainty

Referring to Figure 3-1, the function $f_Y(y)$ is a derived distribution of $f_X(x)$ and they are related by the following expression:

$$f_Y(y) = f_X(x)\left|\frac{dx}{dy}\right|.$$

Where dx and dy are incremental changes in x and y respectively. It is to be noted that the absolute value in the previous equation allows for the relationship between Y and X to be monotonically decreasing, Benjamin *et al* 1970, where X and Y are continuous random variables.

Thus, uncertainty analysis can be defined as the investigation of the probability density functions of inputs, and how their effect on probability density functions of the resulting outputs.

Basis of Uncertainty Analysis

The equation for determining sensitivity factors derived previously can be modified to separate the known value for the perturbation, P, where P is defined as:

$$P = \frac{\delta x}{x^*} \times 100\%,$$

and the uncertainty in the output, U, where U is defined as:

$$U = \frac{\delta y}{y^*} \times 100\%.$$

Again where $\delta y = y' - y^*$. Thus the expression for the sensitivity factor becomes:

$$SF = \frac{U}{P}$$

A series of computer model simulations are performed with perturbations in selected inputs. By maintaining a base case and only varying one variable for each run generally by ± 1, 5, 10, and 20%, the resulting uncertainties in the outputs, U, will be obtained.

Referring to Figure 3-2 ,if the uncertainty is known for a certain input, say $x \pm$ P%, then the uncertainty in the output, $y \pm$ U%, can be estimated from the results obtained, where U is defined previously.

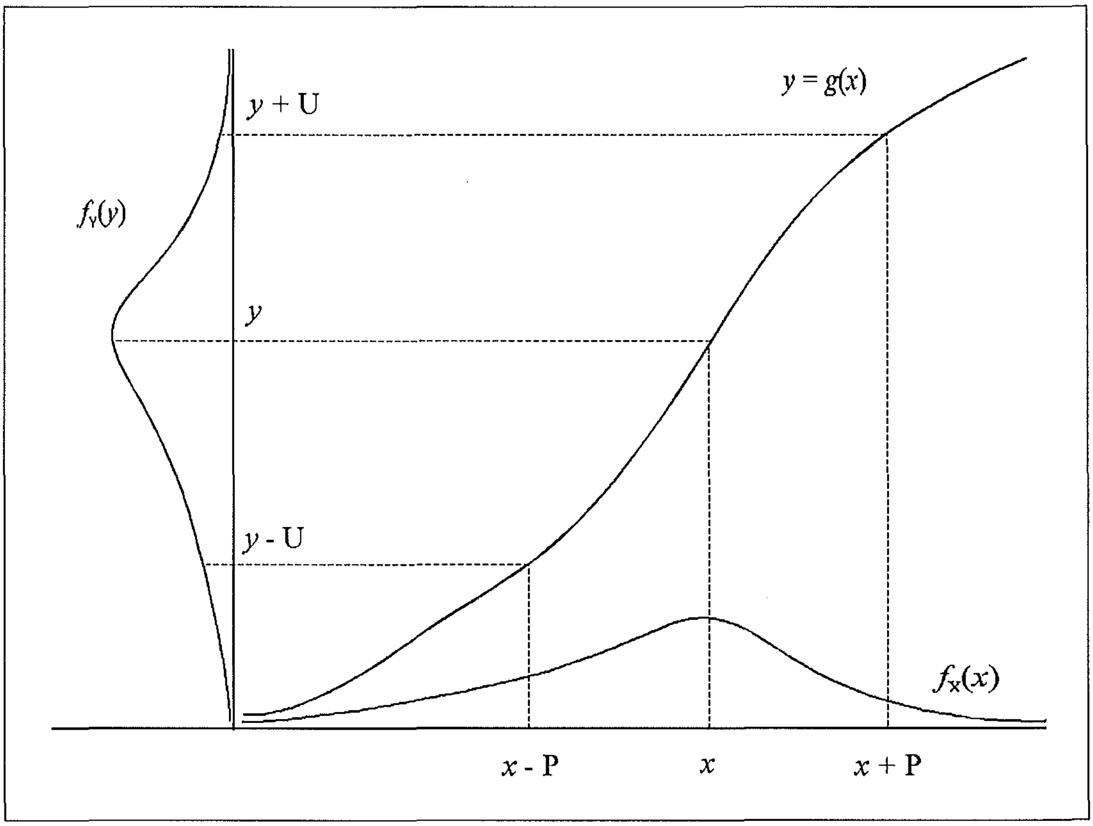


Figure 3-2 Basis of Uncertainty Analysis

Variables identified to be of interest include effects such as building geometry (compartment sizes, surface material properties, vents …), fire specification (fire room, gaseous ignition temperature, radiative fraction, species yields …), and ambient conditions (temperature, pressure, relative humidity).

If a factorial design were to be performed at the eight levels of uncertainty for all combinations of the fourteen selected variables, this would lead to $8^{14} \approx 4.4 \times 10^{12}$ simulations being performed. This number could be reduced somewhat by utilising a fractional factorial design, although this still leads to an immense number of simulations that would be required. For a discussion of factorial designs and fractional factorial designs, the reader is directed to Box *et al* 1978.

Due to the large number of input variables to be analysed , it has been decided to look at each of the selected input variables individually. If pairs of variables were to be investigated, for the fourteen variables there would be 91 combinations, and with eight perturbations, 728 simulations would be required to be run. It should be acknowledged here that some of the input variables may not be independent.

THE CFAST OUTPUT COMPARISON METHOD

The CFAST Output Comparison Method, Alvord 1995, consists of a suite of computer programs that are used to analyse the history file generated by CFAST. It is a multiple step method used to compare output of CFAST simulations. It has been developed at the BFRL to analyse the differences between versions of CFAST.

The CFAST simulations of interest are run and a text file of important output variables is produced for each simulation. The text files are then compared and their differences stored. The last step summarises the difference information.

The output is a series of relative differences between the two CFAST runs. Thus for a 10% increase in heat release rate, the effects on all of the output variables in CFAST can be found.

One characteristic of the suite, is the way in which it constructs the relative differences. The relative difference between two values x and y are defined as:

$$\mathrm{Diff}(x,y) = \frac{\mathrm{Abs}(\,\mathrm{Max}[x,y] - \mathrm{Min}[x,y]\,)}{\mathrm{Abs}(\,\mathrm{Min}[x,y]\,)},$$

or if Min [x,y] = 0,

$$\mathrm{Diff}(x,y) = \frac{\mathrm{Abs}\,(\,\mathrm{Min}\,[x,y]\; - \;\mathrm{Max}\,[x,y]\,)}{\mathrm{Abs}\,(\,\mathrm{Max}\,[x,y]\,)}.$$

These two definitions were created to allow for either of the values for x or y being zero. However whenever this is the case, a relative difference of 1 is returned by the program irrespective of the actual difference between the two values.

It was anticipated that this suite of programs would be used to analyse the results generated by the numerical uncertainty analysis, and hence make the process more time efficient. However, due to compatibility problems with CFAST 3.0 beta versions, and the fact that the version of the suite for CFAST 2.0 can not be implemented on the PC platform, this was abandoned.

Chapter 4 : BaseCases

As detailed in Chapter 3, a series of simulations were performed using CFAST 2.0, with the follow base cases devised. The first basecase was intended to give "generic" results from the model. As there is an infinite range of possibilities available for analysis, it was intended to be a realistic "average" single compartment fire. Areas such as fans and ducts, wind, and sprinkler suppression have been overlooked.

The second basecase was then inspected utilising perturbations in the pertinent input variables identified from the first basecase. This basecase was created to identify areas of large uncertainty when the model is applied to a multicompartment configuration. Again a simple geometry was selected, building on the first basecase to allow for continuity.

The values chosen for the various input variables used in the construction of the basecase data file are discussed.

BaseCase One

A 6×6 m room with 2.7 m stud and one 2×0.8 m door with a fast t^2 fire has been selected. Constructed of gypsum plaster walls and ceiling with a softwood (pine, fir) floor.

The fast t^2 fire selected for the basecase was ventilation limited. The ventilation limit was calculated by the formula:

$$\dot{Q}_{vent} = 1500\,A\sqrt{h}$$

where

$\dot{Q}_{vent}$	ventilation limit [kW]
A	area [m^2]
h	height of opening [m]

The possible effect of compartment enhanced mass loss rate was accommodated by allowing the ventilation limit to reach twice the calculated value, Fleischmann *et al* 1997. This allows for factors such as radiation heating the fuel. This produces a ventilation limited pyrolysis rate higher than that calculated from:

$$\dot{m}_{fuel} = \dot{Q}/\Delta H_c \qquad \dot{Q} < \dot{Q}_{vent}$$

$$\dot{m}_{fuel} = \dot{Q}_{vent}/\Delta H_c \qquad \dot{Q} = \dot{Q}_{vent}$$

where

$\dot{m}_{fuel}$	pyrolysis rate [kg/s]
$\dot{Q}$	heat release rate [kW]
ΔH_c	heat of combustion [kJ/kg]

As Cedit calculates the pyrolysis rate from the previous formulae utilising the user specified Heat Release Rate and Heat of Combustion, the Heat Release Rate entered is levelled off at twice the ventilation limit. The Heat Release Rate of the fire is still limited by CFAST, constrained by the available oxygen. Thus a higher mass loss rate is generated within the compartment.

The Heat of Combustion, ΔH_c, of the fuel was taken to be 18000 kJ/kg for a cellulosic based fuel, Tewarson 1995, table 3-4.16 of the SFPE Handbook.

The Mass Loss Flux, $\dot{m}_{flux}$, of a cellulosic based fuel is taken from Tewarson *et al* 1985 as 0.01 kg/m^{2}s. This variable was then used to calculate the fire area from the following equation

$$A = \dot{m}_{fuel} / \dot{m}_{flux}$$

where

$\dot{m}_{flux}$ mass loss flux [kg/m^{2}s]

The radiative fraction of heat release by the fire, λ_{rad}, was taken as 0.25. Values for radiative fractions generally range from 0.1 to 0.4, Burgess et al 1974. Thus 0.25 was selected as a midrange value.

There is no facility within Cedit for changing the radiative fraction value, and thus the data file must be changed by use of a text editor. Jones 1993 states that the default radiation value is 15%.

Confusion may arise where values are quoted for λ_c, as this symbol is used for both conductive and convective fractions. It is noted that generally convective fractions are used when referring to the plume, and conductive fractions refer heat dissipated that is not radiated.

As a point of interest, Cooper 1982 suggests the following guidelines for selection of a value for λ_{cond}, the fraction of heat lost to the surroundings by conduction, when a reliable estimate of its actual value is not available:

1. λ_{cond} = 0.6, where a conservative estimate of the time to a hazardous temperature or hazardous interface layer.
2. λ_{cond} = 0.9, where a conservative estimate of detection time, where detection is by temperature or rate of temperature rise of the upper layer.

The value of 80% ambient relative humidity was obtained from NIWA in Christchurch. It arises from a value of 76% in Christchurch, 80% around Nelson, up to 83% near Hamilton. These values are averages for 1960 to 1989.

The ambient pressure was left at the default value of 101300 Pa, Jones 1993.

The lower oxygen limit is left at its default value of 10%, Jones 1993, below which there is a non-combustible mixture of pyrolysates and oxygen. However Deal 1994 noted that this value decreases with increasing temperature. No allowance is made within CFAST for this phenomenon.

The hydrogen to carbon ratio, the carbon monoxide to carbon dioxide yield, and the carbon to carbon dioxide yield are taken as 0.167, 0.003, and 0.012 respectively. These values are taken from Tewarson 1995, table 3-4.16 of the SFPE Handbook. Due to a limitation within the data file produced by Cedit, these values are restricted to three decimal places.

The facility to provide information on the oxygen mass fraction of the fuel has not been included in the data file. This is due to the fact that the oxygen parameter does not work, Jones 1997.

Input Variable Perturbations

Unless otherwise stated, for ± 1, 5, 10, and 20% perturbations, the following variables have been considered for this case.

1. Heat Release Rate, $\dot{Q}$. (Fast t^2 fire)
2. Heat of Combustion, ΔH_c. (= 18000 [kJ/kg])
3. Mass Loss Flux. (= 0.01 [kg/m²s])
4. Radiative Fraction. (= 25%)
5. Ambient Temperature. (= 20°C)
6. Ambient Relative Humidity.(= 80%)
7. Ambient Pressure. (= 101300 Pa)
8. Lower Oxygen Limit. (= 10%)
9. H/C ratio. (= 0.167)
10. CO/CO_2 yield. (= 0.003)
11. C/CO_2 yield. (= 0.012)
12. Vent Height. (= 2 [m])
13. Vent Width. (= 0.8 [m])
14. Ceiling Height. (= 2.7 [m])

A one off scenario will also be investigated to determine how CFAST 2.0 compares to the beta release version of CFAST 3.0.

The Heat Release Rate was identified as an obvious influence in the results produced by a zone fire model. Changes to the HRR resulted in the ventilation limit and fire area being reached at differing times.

Perturbations in the Heat of Combustion allowed for a change in pyrolysis rate, and hence a change in fire area, while the Mass Loss Flux perturbations resulted in changes to the fire area only.

Due to the limitation placed on the carbon to carbon dioxide yield variable, perturbations of ± 8, and 16%, resulting in values of 0.010, 0.011, 0.012 (basecase), 0.013, and 0.014 were used.

Similarly, the limitation placed on the carbon monoxide to carbon dioxide yield variable, perturbations of ± 33% resulting in values of 0.002, 0.003 (basecase), and 0.004 were used.

It was observed that Cedit formats the value for ambient pressure to only two significant figures. This, however is not the case in the data file, where the accuracy is maintained to the nearest whole Pascal. The ±20 % perturbations are not included, as they are too extreme to be physically meaningful.

Output Variables Considered

The following CFAST output variables have been considered in this analysis.

1. Interface layer height.
2. Temperature of the upper layer.
3. Temperature of the lower layer.
4. Heat release rate of the fire.
5. Plume mass entrainment.
6. Vent upper mass flow rate.
7. Vent lower mass flow rate.

8. Vent fire heat release rate.
9. Radiation from the upper layer.
10. Convection from the upper layer.
11. Species concentration of oxygen in the upper layer.
12. Species concentration of oxygen in the lower layer.
13. Species concentration of carbon dioxide in the upper layer.
14. Species concentration of carbon dioxide in the lower layer.
15. Species concentration of carbon monoxide in the upper layer.
16. Species concentration of carbon monoxide in the lower layer.

BaseCase One Data File

```
VERSN  2ONE COMPARTMENT BASE CASE
TIMES  900   10   10   10   0
TAMB   293.  101300.    0.
EAMB   293.  101300.    0.
HI/F   0.00
WIDTH  6.00
DEPTH  6.00
HEIGH  2.70
HVENT  1  2  1   0.800   2.000   0.000   0.000
CVENT  1  2  1   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00  1.00  1.00  1.00   1.00  1.00  1.00  1.00
CEILI  GYPSUM
WALLS  GYPSUM
FLOOR  SOFTWOOD
CHEMI  30.  80.  10.0   18000000.  293. 493. 0.250
LFBO   1
LFBT   2
FPOS   3.00  3.00  0.50
FTIME  10.   20.   30.   40.   50.   60.   90.   120.   150.   180.   210.   240.   270.
300.  330.  372.  380.  900.
FMASS  0.0000 0.0003 0.0010 0.0024 0.0041 0.0065 0.0094 0.0211 0.0375 0.0585
0.0842 0.1153 0.1502 0.1898 0.2340 0.2834 0.3600 0.3771 0.3771
FHIGH  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00  0.00  0.00  0.00  0.00  0.00
FAREA  0.00  0.03  0.10  0.23  0.42  0.65  0.94  2.11  3.75  5.86  8.44  11.49  15.01
18.99  23.45  28.37  36.00  36.00  36.00
FQDOT  0.00    4.70E+03 1.88E+04 4.22E+04 7.50E+04 1.17E+05 1.69E+05 3.80E+05
6.75E+05  1.06E+06  1.52E+06  2.07E+06  2.70E+06  3.42E+06  4.22E+06  5.11E+06
6.48E+06 6.79E+06 6.79E+06
CJET   ALL
HCR    0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167
0.167 0.167 0.167 0.167 0.167 0.167
```

```
CO       0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003
0.003 0.003 0.003 0.003 0.003 0.003
OD       0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012
0.012 0.012 0.012 0.012 0.012 0.012
STPMAX        5.00
DUMPR         BASE20.HI
DEVICE        1
WINDOW   0   0.   0. 1279. 1023. 4095.
```

BASECASE TWO

Basecase one is adapted to include a corridor connecting to another room of the same size. The corridor is arbitrarily taken as 6 meters long and two meters wide, with a door width equal to twice that of each of the compartments, at 1.6 meters wide.

Input Variable Perturbations

The following variables have been considered for the second basecase, again for ±1, 5, 10, and 20% perturbations. These input variables have been identified by the previous basecase to be those that result in the most uncertainty in the initial period of the simulation, where life safety is of most importance.

1. HRR.
2. Radiative Fraction. (= 25%)
3. Ambient Temperature. (= 20°C)
4. Ambient Pressure. (= 101300 Pa)
5. Ceiling Height. (= 2.7 [m])

Output Variables Considered

The following CFAST output variables have been considered in this analysis. The set identified here is different to the set of variables identified in the first basecase, as these are the variables required to determine life safety.

1. Interface layer height.
2. Temperature of the upper layer.
3. Temperature of the lower layer.
4. Species concentration of carbon dioxide in the upper layer.
5. Species concentration of carbon dioxide in the lower layer.
6. Species concentration of carbon monoxide in the upper layer.
7. Species concentration of carbon monoxide in the lower layer.

BaseCase Two Data File

```
VERSN  2THREE COMPARTMENT BASECASE
TIMES  900  10  10  10  0
TAMB   293. 101300.  0.
EAMB   293. 101300.  0.
HI/F   0.00  0.00  0.00
WIDTH  6.00  6.00  6.00
DEPTH  6.00  2.00  6.00
HEIGH  2.70  2.70  2.70
HVENT  1 2 1  0.800  2.000  0.000
HVENT  2 3 1  0.800  2.000  0.000
HVENT  2 4 1  1.600  2.000  0.000  0.000
CVENT  1 2 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  2 3 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  2 4 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
CEILI  GYPSUM  GYPSUM  GYPSUM
WALLS  GYPSUM  GYPSUM  GYPSUM
FLOOR  SOFTWOOD SOFTWOOD SOFTWOOD
CHEMI  30.  80.  10.0  18000000. 293. 493. 0.250
LFBO   1
LFBT   2
FPOS   3.00  3.00  0.50
```

```
FTIME  10.  20.  30.  40.  50.  60.  90.  120.  150.  180.  210.  240.  270.
300.  330.  372.  380.  900.
FMASS  0.0000 0.0003 0.0010 0.0024 0.0041 0.0065 0.0094 0.0211 0.0375 0.0585
0.0842 0.1153 0.1502 0.1898 0.2340 0.2834 0.3600 0.3771 0.3771
FHIGH  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00  0.00  0.00  0.00  0.00  0.00
FAREA  0.00  0.03  0.10  0.23  0.42  0.65  0.94  2.11  3.75  5.86  8.44  11.49  15.01
18.99  23.45  28.37  36.00  36.00  36.00
FQDOT  0.00    4.70E+03   1.88E+04   4.22E+04   7.50E+04   1.17E+05   1.69E+05
3.80E+05 6.75E+05  1.06E+06  1.52E+06  2.07E+06  2.70E+06  3.42E+06  4.22E+06
5.11E+06 6.48E+06  6.79E+06  6.79E+06
CJET     ALL
HCR      0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167 0.167
0.167 0.167 0.167 0.167 0.167 0.167 0.167
CO       0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003 0.003
0.003 0.003 0.003 0.003 0.003 0.003 0.003
OD       0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012 0.012
0.012 0.012 0.012 0.012 0.012 0.012 0.012
STPMAX   5.00
DUMPR    3RBASE.
DEVICE   1
WINDOW   0  0.   0. 1279. 1023. 4095.
```

Chapter 5 : RESULTS AND DISCUSSION

Presented here is a series of graphs representing the effect of uncertainty in various input variables on a set of selected output variables. Those selected are representative of the entire results for the first basecase, and are included in Appendix A. The reproduction of the results *ad nauseam* in the appendix is intended to act as a ready reference guide. The results for the second basecase are then presented as a series of tables containing information on times required to reach set tenability limits.

BASECASE ONE

These results are representative and are used as an explanation to enable interpretation of the remaining results.

Compartment Conditions

The following graphs are of the conditions in the compartment for the variables tracked in the output. Although not apparent in Figure 5-2, the lower layer temperature drops below the ambient temperature of 20 °C to approximately 15 °C. Conversely, the slight noticeable increase in the lower layer oxygen concentration in Figure 5-6 is actually due to the graphics resolution, and does not occur in the data.

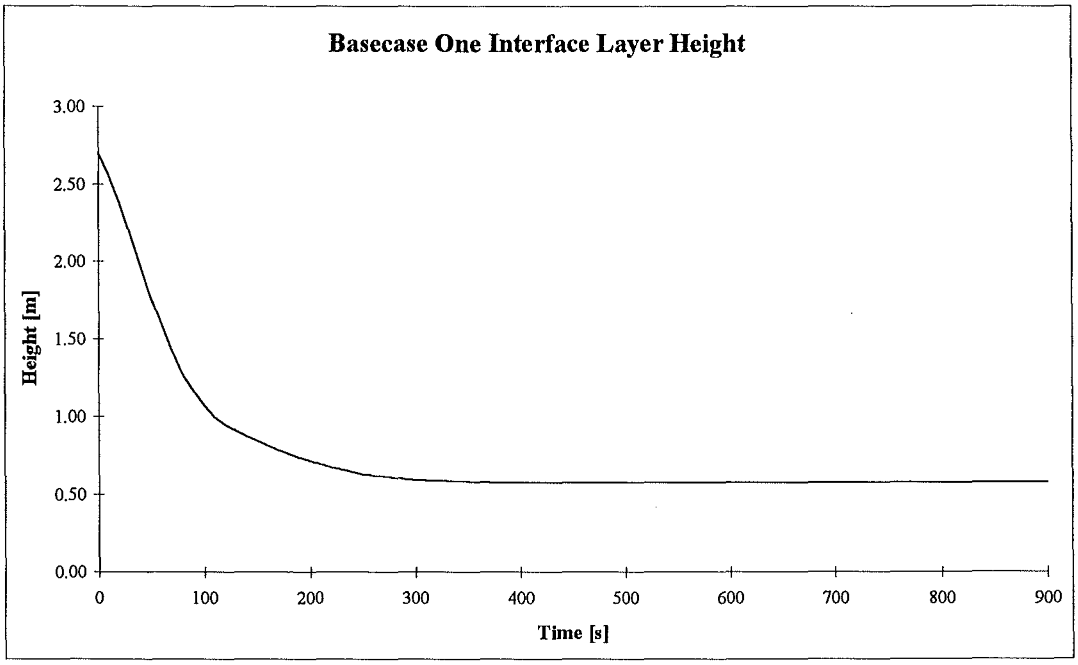


Figure 5-1 Basecase One Interface Layer Height

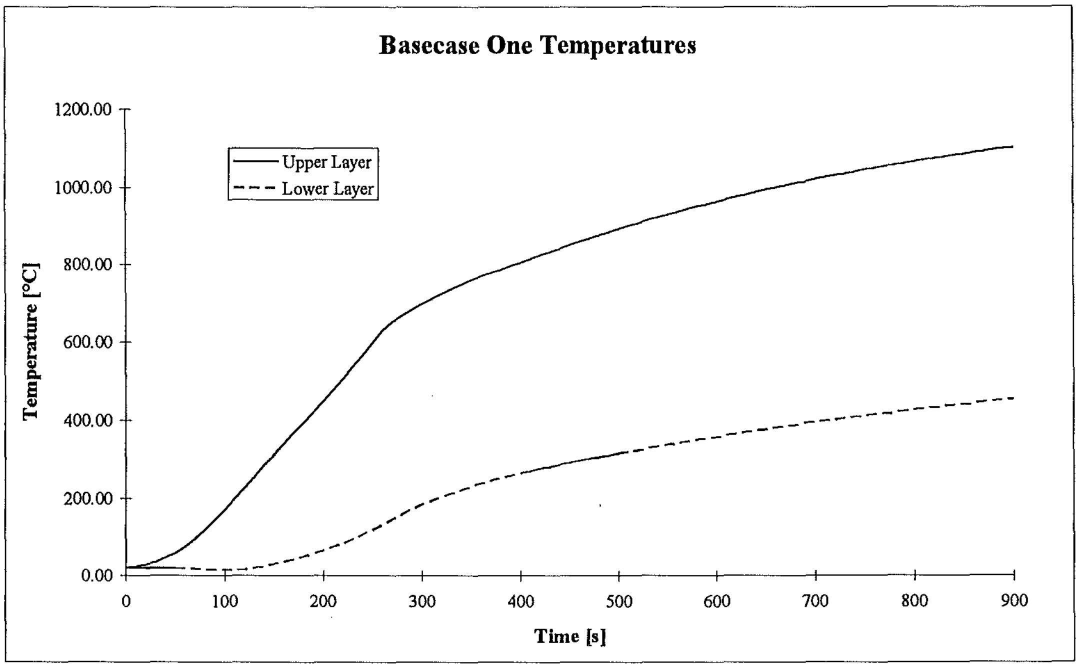


Figure 5-2 Basecase One Temperatures

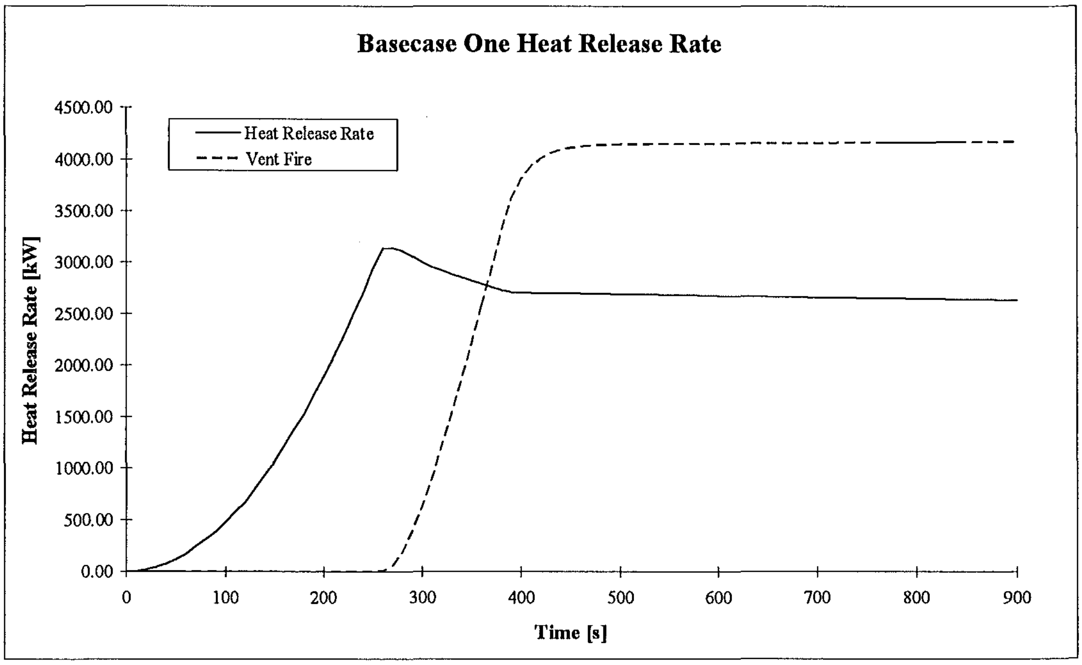


Figure 5-3 Basecase One Heat Release Rate

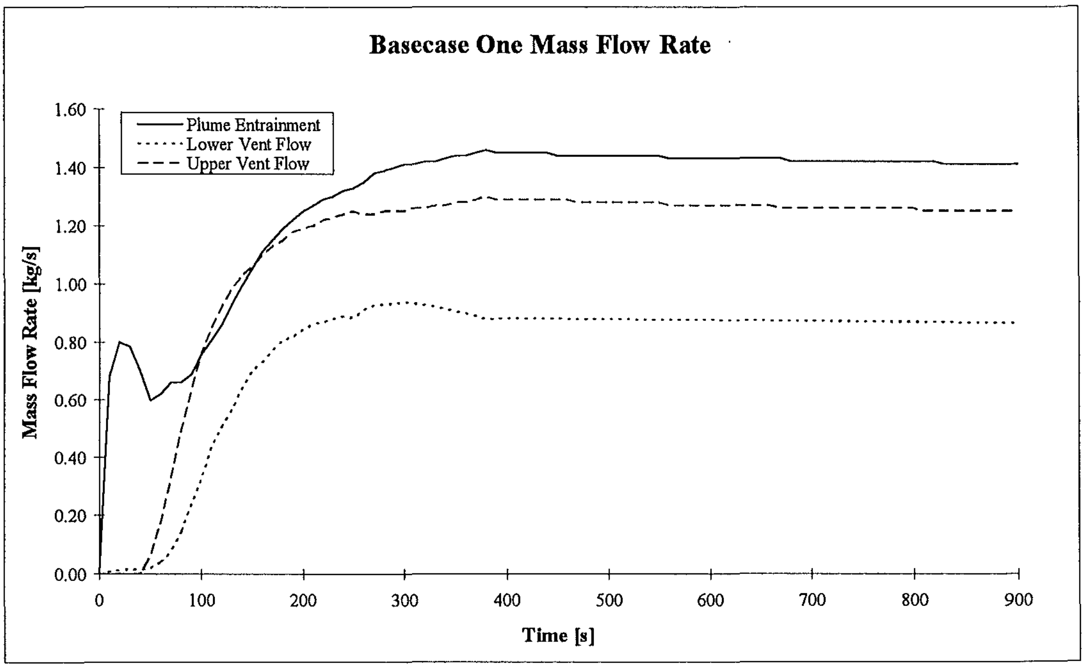


Figure 5-4 Basecase One Mass Flow Rate

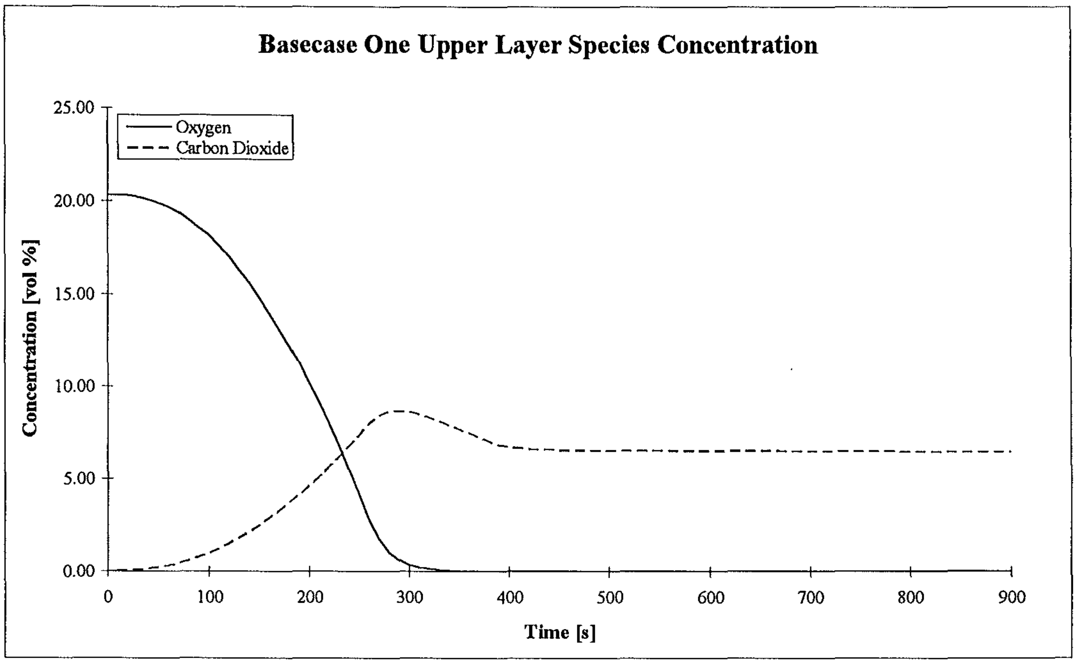


Figure 5-5 Basecase One Upper Layer Species Concentration

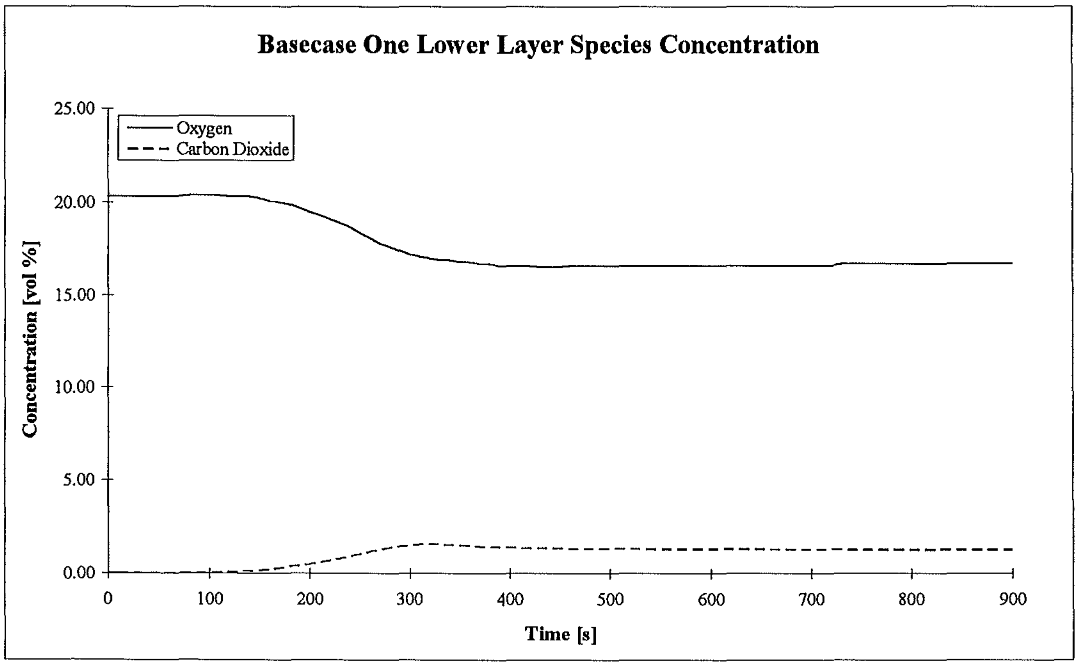


Figure 5-6 Basecase One Lower Layer Species Concentration

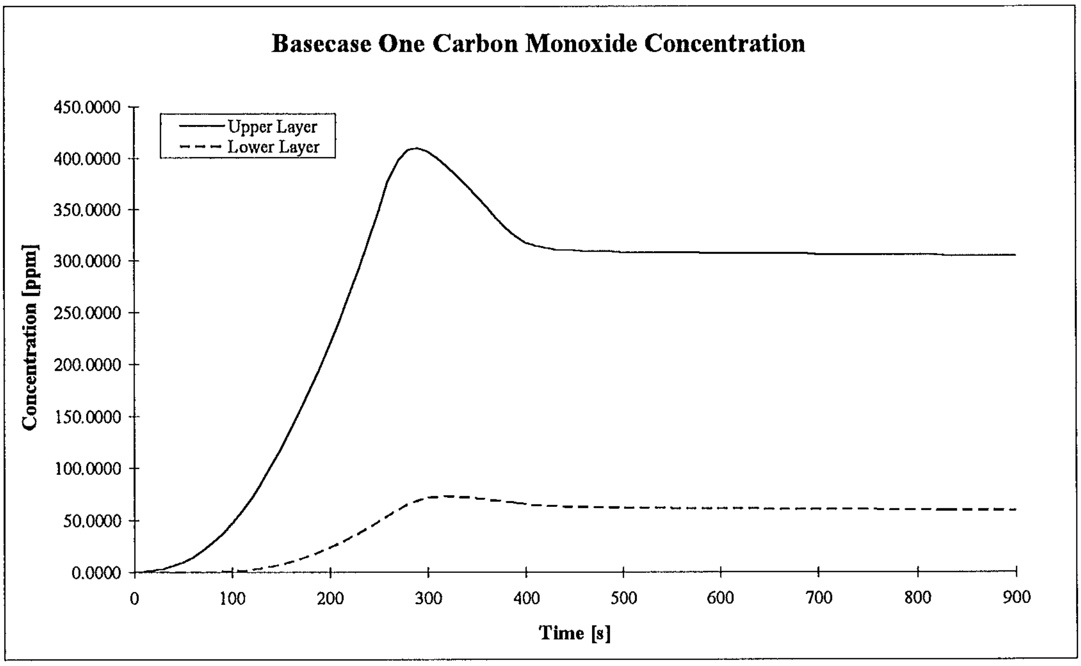


Figure 5-7 Basecase One Carbon Monoxide Concentration

BaseCase One Characteristic Results

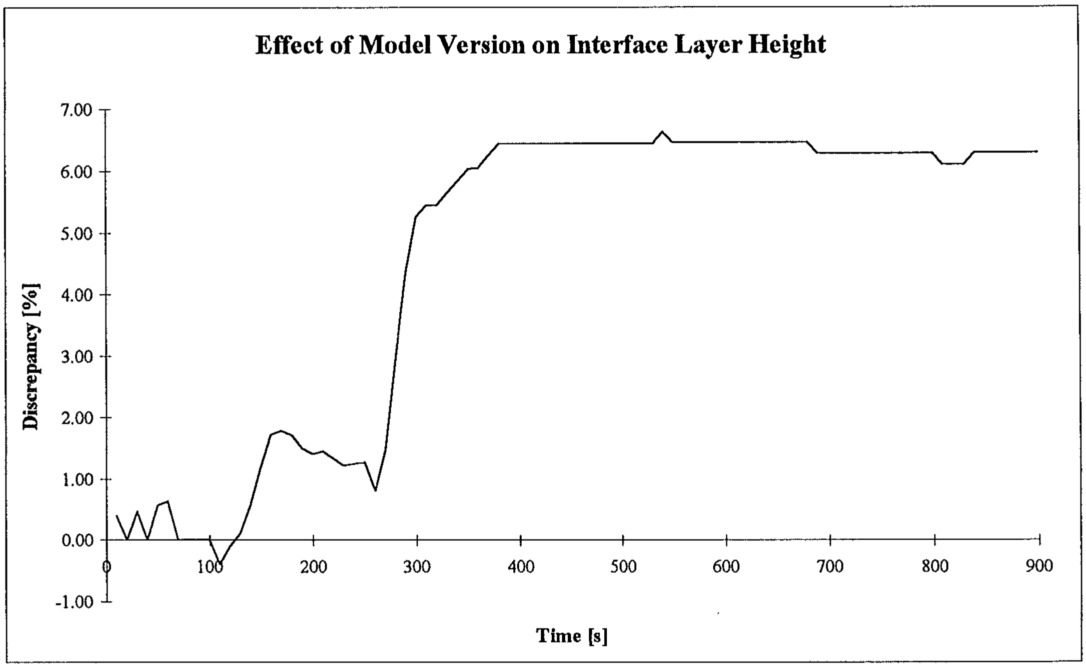


Figure 5-8 Effect of Model Version on Interface Layer Height

Figure 5-8 indicates that CFAST 3.0 reaches a steady state interface layer height that is 6 ~ 7% higher than CFAST 2.0.

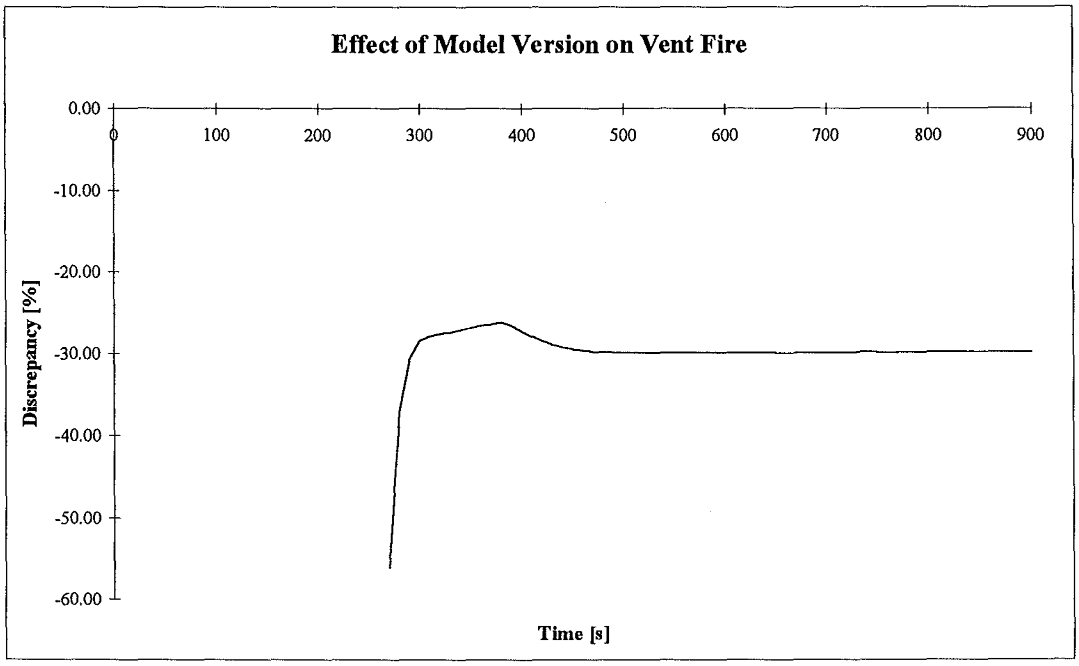


Figure 5-9 Effect of Model Version on Vent Fire

In Figure 5-9, the discrepancy between the two models occurs after 260 seconds of simulation time. The high initial value is due to CFAST 3.0 not having a vent fire at that time. Thus no discrepancy exists before this point.

A similar phenomenon occurs for the oxygen concentration in the upper layer, as seen in Figure 5-10. Here the two models become oxygen limited by 300 seconds, but at slightly different times, leading to a large discrepancy at this point.

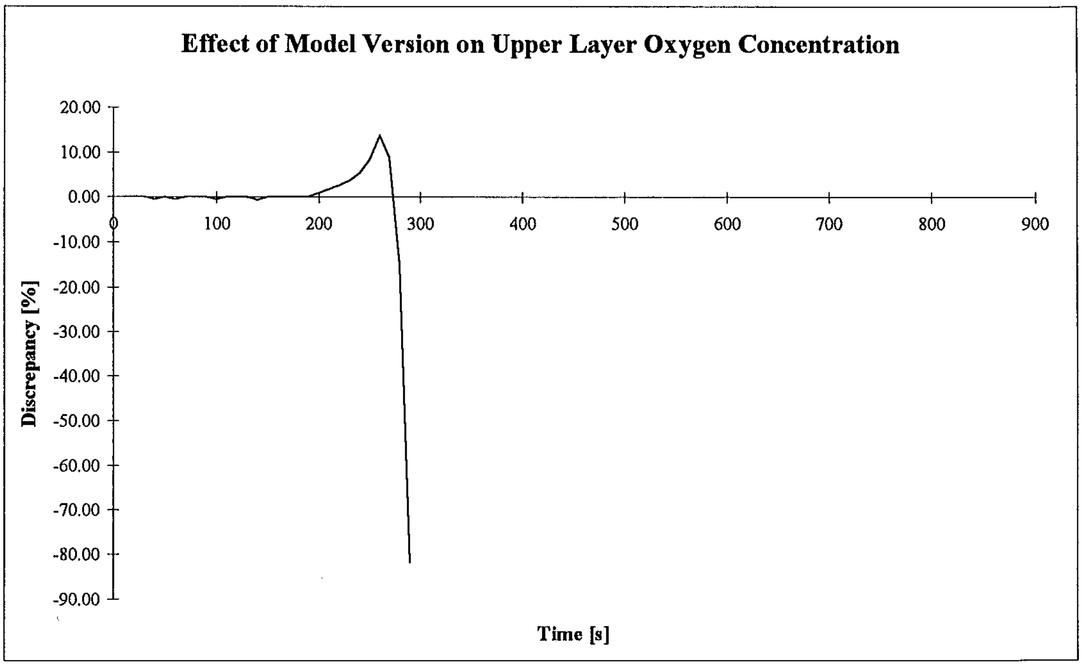


Figure 5-10 Effect of Model Version on Upper Layer Oxygen Concentration

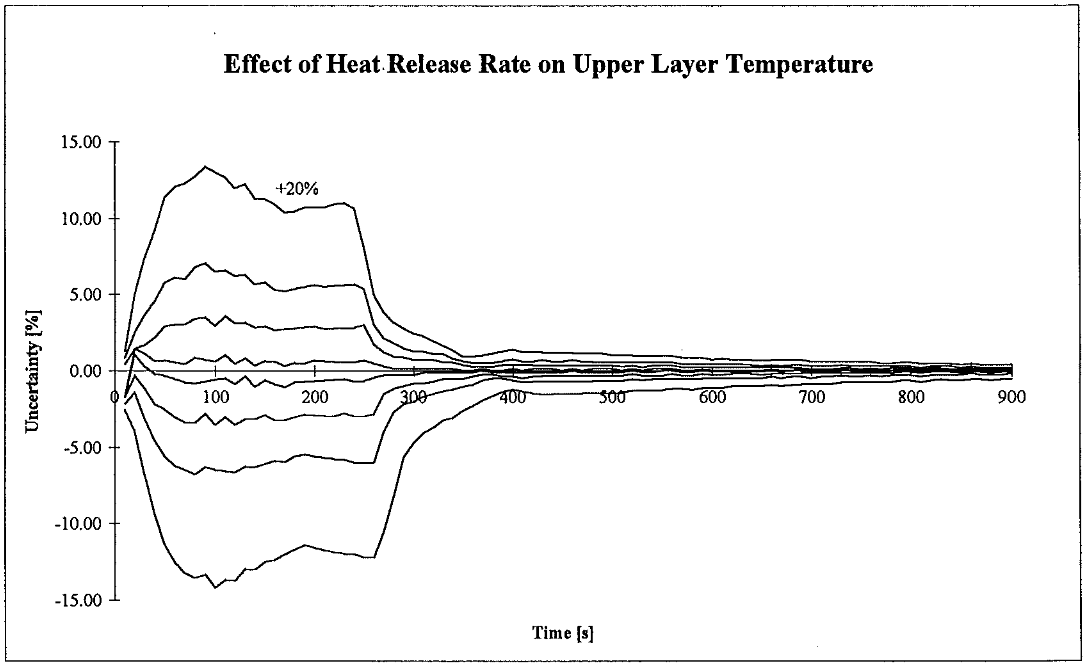


Figure 5-11 Effect of Heat Release Rate on Upper Layer Temperature

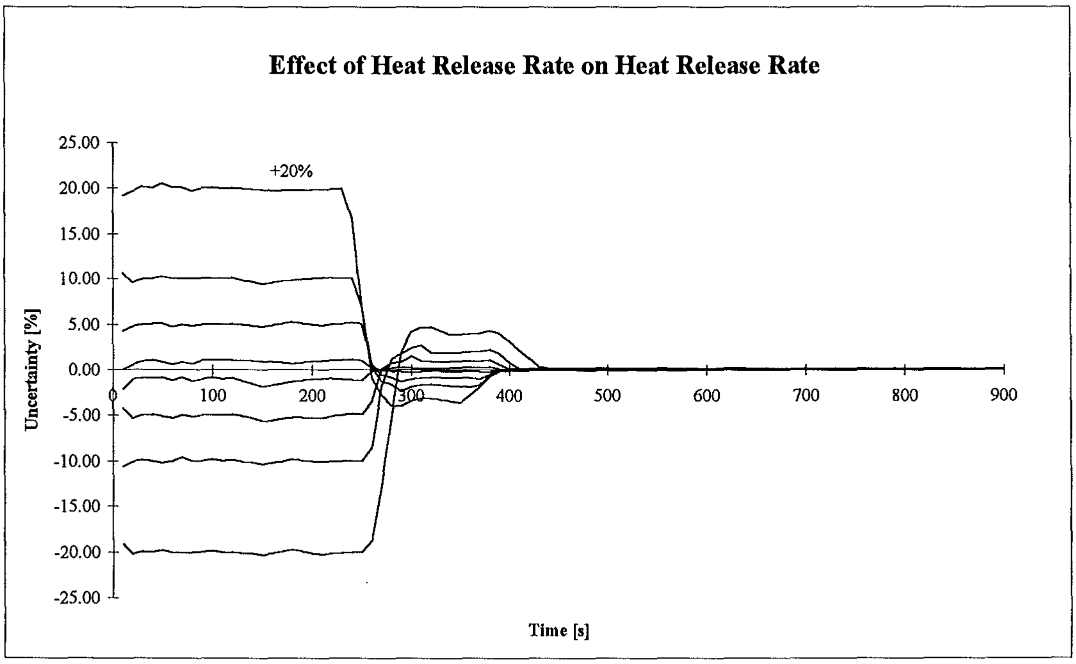


Figure 5-12 Effect of Heat Release Rate on Heat Release Rate

From the previous two graphs, Figure 5-11 and Figure 5-12, where the "+20%" indicates the perturbation (the remaining can be easily identified), the following can be deduced. A ± 20% uncertainty in heat release rate results in a maximum ± 13 to 14% uncertainty in the upper layer temperature. However, as the simulation proceeds, the uncertainty diminishes. A ± 20% uncertainty in heat release rate results in a ± 20% in the heat release rate, as the compartment fire becomes ventilation limited all of the fires are confined by the vent geometry.

This identifies the main drawback of the numerical analysis method adopted, the uncertainties are purely those that exist in the model, and are not indicative of the uncertainties corresponding to comparisons of the model with reality. This situation arises due to the selection of a basecase as a basis for comparison.

All of the graphs can be interpreted in this manner, and inspection will yield supporting fire phenomenon for the trends observed. However, there are several variables that result in graphs of the appearance of Figure 5-13. No matter what the perturbation for these simulations, the results are identical. The CFAST data files have been checked for any errors, and no anomalies have been found.

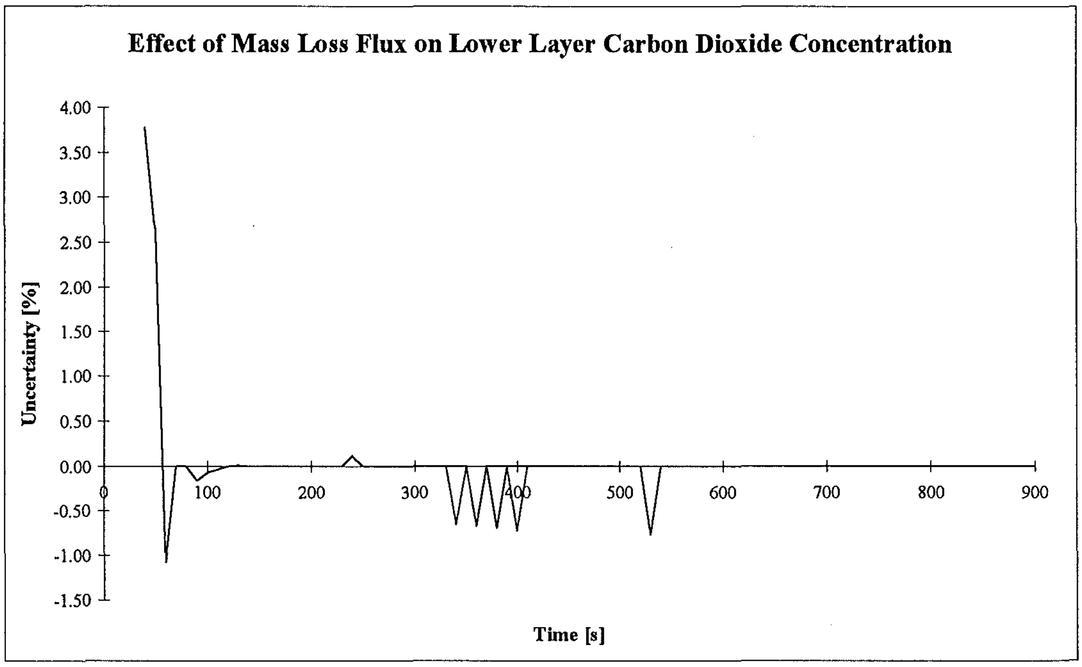


Figure 5-13 Effect of Mass Loss Flux on Lower Layer Carbon Dioxide Concentration

BASECASE TWO

Definition of Tenability

The following definitions for untenable conditions are taken from Purser 1995.

Interface Layer Height: is taken to be the time at which the interface layer reaches a height of 1.5 meters, this is due to smoke obscuration resulting in disorientation.

Upper Layer Temperature: is taken to be the time at which the upper layer reaches a temperature of 200 °C, this is the point at which radiation from the upper layer reaches 0.25 [kW/m^2], resulting in pain after 30 to 60 seconds.

Lower Layer Temperature: is taken to be the time at which the lower layer reaches a temperature of 100 °C, this is the point where the laryngeal tract sustains burns, resulting in death due to obstructive edema of the laryngopharynx within a few hours of exposure.

Carbon Dioxide Concentration: is taken to be the time at which the atmosphere that would be inhaled has a concentration of carbon dioxide exceeding 5% by volume. Incapacitation would result after 30 minutes of light activity, e.g. walking.

Carbon Monoxide Concentration: is taken to be the time at which the atmosphere that would be inhaled has a concentration of carbon dioxide exceeding 1400 ppm by volume. Incapacitation would result after 30 minutes of light activity, e.g. walking.

	Interface	Temp (up)	Temp (low)	CO_2 (up)	CO_2 (low)	CO (up)	CO (low)
-20%	150	830	900	420	900	900	900
-10%	140	820	900	400	900	900	900
-5%	140	820	900	400	900	900	900
-1%	140	810	900	390	900	900	900
BC	**140**	**810**	**900**	**390**	**900**	**900**	**900**
1%	140	810	900	390	900	900	900
5%	140	810	900	390	900	900	900
10%	140	800	900	380	900	900	900
20%	130	800	900	370	900	900	900

Table 5.1 Effect of Heat Release Rate on Time to Tenability in Room Three

	Interface	Temp (up)	Temp (low)	CO_2 (up)	CO_2 (low)	CO (up)	CO (low)
-20%	140	810	900	390	900	900	900
-10%	140	810	900	390	900	900	900
-5%	140	810	900	390	900	900	900
-1%	140	810	900	390	900	900	900
BC	**140**	**810**	**900**	**390**	**900**	**900**	**900**
1%	140	810	900	390	900	900	900
5%	140	810	900	390	900	900	900
10%	140	810	900	390	900	900	900
20%	140	810	900	390	900	900	900

Table 5.2 Effect of Radiative Fraction on Time to Tenability in Room Three

	Interface	Temp (up)	Temp (low)	CO_2 (up)	CO_2 (low)	CO (up)	CO (low)
-20%	140	820	900	390	900	900	900
-10%	140	820	900	390	900	900	900
-5%	140	820	900	390	900	900	900
-1%	140	810	900	390	900	900	900
BC	**140**	**810**	**900**	**390**	**900**	**900**	**900**
1%	140	810	900	390	900	900	900
5%	140	810	900	390	900	900	900
10%	140	810	900	390	900	900	900
20%	140	800	900	390	900	900	900

Table 5.3 Effect of Ambient Temperature on Time to Tenability in Room Three

	Interface	Temp (up)	Temp (low)	CO_2 (up)	CO_2 (low)	CO (up)	CO (low)
-10%	140	900	900	390	900	900	900
-5%	140	900	900	390	900	900	900
-1%	140	830	900	390	900	900	900
BC	**140**	**810**	**900**	**390**	**900**	**900**	**900**
1%	140	790	900	390	900	900	900
5%	140	760	900	400	900	900	900
10%	150	760	900	400	900	900	900

Table 5.4 Effect of Ambient Pressure on Time to Tenability in Room Three

	Interface	Temp (up)	Temp (low)	CO_2 (up)	CO_2 (low)	CO (up)	CO (low)
-20%	120	550	790	320	900	900	900
-10%	130	680	900	350	900	900	900
-5%	140	750	900	370	900	900	900
-1%	140	800	900	390	900	900	900
BC	**140**	**810**	**900**	**390**	**900**	**900**	**900**
1%	140	830	900	400	900	900	900
5%	140	900	900	420	900	900	900
10%	140	900	900	430	900	900	900
20%	150	900	900	480	900	900	900

Table 5.5 Effect of Ceiling Height on Time to Tenability in Room Three

Inspection of the preceding tables yield the same conclusion. There appears to be very little dependency on the time to untenability due to the interface layer height in this situation. The effects due to heat release rate and ceiling height show ± 10 seconds for input uncertainties of ± 20 %.

The upper layer carbon dioxide concentration is the only one of the gaseous species tenability limits that is exceeded within the simulation timeframe, and shows uncertainty when influenced by heat release rate and ceiling height.

Chapter 6 : CONCLUSIONS

It is urged that practising fire engineers using zone models are aware of the necessity to acknowledge the existence of uncertainty within the results obtained. The objective being to make fire engineers aware of the degree of uncertainty involved within the results obtained, specifically those of prime interest such as the variables related to identifying life threatening conditions.

It was found from the analysis that uncertainty in the heat release rate, radiative fraction, ambient temperature, ambient pressure, and ceiling height resulted in discernible uncertainty in the output.

It should also be noted that the uncertainties are purely those that exist in the model, and are not indicative of the uncertainties corresponding to comparisons of the model with reality.

Another point that arises when analysing the results is that no assumptions are made as to the dependency of the variables, nor to their correlation. To acquire this information would require thousands of simulations.

When the same method was applied to analysis of time to reach untenable conditions in a multiple room configuration, it was found that the time step used for output intervals to the history file created by CFAST was an overbearing factor. However it was found that uncertainties in the heat release rate and the compartment ceiling height propagated through to the results.

Future Research

A similar analysis could performed next year once the completed version of CFAST 3.0 has been released. It was expected that this would be in February 1997. If it were found that CFAST 3.0 behaved as expected, then this may result in CFAST 3.0 being accepted by the Territorial Authorities as an acceptable tool for use in Alternative Solutions.

REFERENCES

Alvord, D. M. 1995, "A CFAST Output Comparison Method and its use in Comparing Different CFAST Versions", NISTIR 5705, August 1995, National Institute of Standards and Technology, Gaithersburg, MD.

Babrauskas, V. 1995, "The Generation of CO in Bench-scale Fire Tests and the Prediction for Real-scale Fires", Fire and Materials, Vol. 19, pp. 205-213.

Babrauskas, V. 1996, "Fire Modelling Tools for FSE: Are They Good Enough?", J. of Fire Prot. Engr, Vol. 8, No. 2, pp. 87-96.

Benjamin, J. R., Cornell, C. A. 1970, "Probability, Statistics, and Decision for Civil Engineers", McGraw-Hill Book Company, 684 p.

Box, G. E. P., Hunter, W. G., Hunter, J. S. 1978, "Statistics for Experimenters; an Introduction to Design, Data Analysis, and Model Building", John Wiley & Sons, 653 p.

Brani, D. M., Black, W. Z. 1992, "Two-Zone Model for a Single-Room Fire", Fire Safety Journal, Vol. 19, No. 3, pp. 189-216.

Buchanan, A. H. 1995, "Fire Engineering Design Guide", Centre for Advanced Engineering, University of Canterbury.

Burgess, D., Hertzberg, M. 1974, "Radiation from Pool Fires", from *Heat Transfer in Flames*, chapter 27, John Wiley & Sons.

Cooper, L. Y. 1982, "A Mathematical Model for Estimating Available Safe Egress Time", Fire and Materials, Vol. 6, No. 4, pp. 135-144.

Deal, S. 1994, "Technical Reference Guide for FPEtool Version 3.2", NISTIR 5486, August 1994, National Institute of Standards and Technology, Gaithersburg, MD.

Drysdale, D. D. 1995, "Thermochemistry", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 1-5, National Fire Protection Association.

Evans, D. D. 1993, "Sprinkler Fire Suppression Algorithm for HAZARD", NISTIR 5254, August 1993, National Institute of Standards and Technology, Gaithersburg, MD.

Fleischmann, C. M., Parkes, A. R. 1997, "Effects of Ventilation on the Compartment Enhanced Mass Loss Rate", Fire Safety Science, Proceedings of the Fifth International Symposium.

Jones, W. W., Peacock, R. D., Forney, G. P., Reneke, P. A., Portier, R. W. 1993, "CFAST, the Consolidated Model of Fire and Smoke Transport", NIST Technical Note 1299, February 1993, National Institute of Standards and Technology, Gaithersburg, MD.

Jones, W. W. 1996, personal communication, 13 TH September 1996.

Jones, W. W. 1997, personal communication, 13 TH January 1997.

McCaffrey, B. J. 1983, "Momentum Implications for Buoyant Diffusion Flames", Combustion and Flame, Vol. 52, pp. 149-167.

Peacock, R. D., Reneke, P. A., Forney, C. L., Kostreva, M. M. "Issues in Evaluation of Complex Fire Models", unpublished, National Institute of Standards and Technology, Gaithersburg, MD.

Purser, D. A. 1995, "Toxicity Assessment of Combustion Products", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 2-8, National Fire Protection Association.

Quintiere, J. G. 1993, "A Simulation Model for Fire Growth on Materials Subject to a Room-Corner Test", Fire Safety Journal, Vol. 20, No. 4, pp. 311-339.

Smith, J. M., Van Ness, H. C. 1987, "Introduction to Chemical Engineering Thermodynamics", McGraw-Hill Book Co., 698 p.

Tewarson, A., Newman, J. S. 1985, "Scale Effects on Fire Properties of Materials", Fire Safety Science, Proceedings of the First International Symposium, pp 451 - 462.

Tewarson, A. 1995, "Generation of Heat and Chemical Compounds in Fires", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 3-4, National Fire Protection Association.

BIBLIOGRAPHY

Baird, D. C. 1962, "Experimentation: An Introduction to Measurement Theory and Experiment Design", Prentice-Hall, Inc., 198 p.

Beard, A. 1992(a), "Evaluation of Deterministic Fire Models: Part 1 - Introduction", Fire Safety Journal, Vol. 19, No. 4, pp. 295-306.

Beard, A. 1992(b), "Limitations of Computer Models", Fire Safety Journal, Vol. 18, No. 4, pp. 375-391.

Beard, A. 1994, "Limitations of Computer Modelling", University of Salford and Association of Building Engineers, Fire Safety Modelling and Building Design, Proceedings, One-Day Conference to Review the Potential and Limitations of Fire Safety Models for Building Design, March 29, 1994, pp. 10-26, Edinburgh University, Scotland.

Beard, A. 1996, "Limitations of Fire Models", J. Applied Fire Science, Vol. 5, No. 3, pp. 233-243.

Beck, V., Yung, D., He, Y., Simathipala, K. 1996, "Experimental Validation of a Fire Growth Model", International Interflam Conference, 7th Proceedings. March 26-28, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, pp. 653-662.

Beller, D. 1996, "Validating Fire Models: FPEtool, CFAST, WPI/FIRE", International Interflam Conference, 7th Proceedings. March 26-28, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, pp. 959-963.

Clement, J. 1995, "The Limitations of Zone Modelling", University of Canterbury, unpublished.

Collier, P. C. R. 1996, "Fire in a Residential Building: Comparisons Between Experimental Data and a Fire Zone Model", Fire Technology Third Quarter.

Davies, A. D. 1985, "Applied Model Validation", NBSIR 85-3154-1, 31p. July 1985, National Bureau of Standards, Gaithersburg, MD.

Davies, A. D. 1987, "Some Tools for Fire Model Validation", Fire Technology, Vol. 23, No. 2, pp. 95-114, May 1987.

Dembsey, N. A., Pagni, P. J., Williamson, R. B. 1995(a), "Compartment Fire Experimental Data: Comparisons to Models", International Conference on Fire Research and Engineering, 10 - 15 September 1995, Orlando, Fl., pp 350-355.

Dembsey, N. A., Pagni, P. J., Williamson, R. B. 1995(b), "Compartment Fire Experiments: Comparison with Models", Fire Safety Journal, Vol. 25, No. 2, pp. 187-227.

Duong, Duy Q. 1990, "The Accuracy of Computer Fire Models: Some Comparisons with Experimental Data from Australia", Fire Safety Journal, Vol. 16, No. 6, pp. 415-431.

Evans, D. D. 1996, "Large Fire Experiments for Fire Model Evaluation", International Interflam Conference, 7th Proceedings. March 26-28, Cambridge, England, Interscience Communications Ltd., London, England, Franks, C. A.; Grayson, S., Editors, pp. 329-334.

Heskestad, G. 1995, "Fire Plumes", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 2-2, National Fire Protection Association.

Ishino, O., Tanaka, T., Delichatsios, M. A. 1995, "Validation of Zone Models : Entrainment rates and Convective Heat Losses from Model Atria Tests", Fire Safety Science, Proceedings of the Fourth International Symposium, pp. 481-492.

Keski-Rahkonen, O. 1996, "A Comparison of Fire Simulation Tools", Open International Symposium on Fire Safety Design and Fire Safety Engineering, 19-20 August 1996, Oslo, Norway.

Kostreva, M. M. 1996, "Sensitivity Analysis for Mathematical Modelling of Fires in Residential Buildings", NIST-GCR-95-683, 14 p. February 1996. Clemson University, SC.

Kostreva, M. M., Jarvis, J. P. 1989, "Graphical Presentation and Numerical Analysis of Fire Data for Model Validation", unpublished, National Institute of Standards and Technology, Gaithersburg, MD.

Mitler, H. E., Rockett, J. A. 1986, "How Accurate is Mathematical Fire Modelling", NBSIR 86-3459, 50 p. December 1986, National Bureau of Standards, Gaithersburg, MD.

Portier, R. W., Peacock, R. D., Reneke, P. A. 1996, "FASTLite: Engineering Tools for Estimating Fire Growth and Smoke Transport", Special Publication 899, April 1996, National Institute of Standards and Technology, Gaithersburg, MD.

Peacock, R. D., Jones, W. 1993, "Verification of a Model of Fire and Smoke Transport", Fire Safety Journal, Vol. 21, No. 2, pp. 89-129, 1993.

Portier, R. W., Reneke, P. A., Jones, W. W., Peacock, R. D. 1992, "A User's Guide for CFAST Version 1.6", NISTIR 4985, December 1992, National Institute of Standards and Technology, Gaithersburg, MD.

Peacock, R. D., Babrauskas, V. 1992, "Heat Release Rate: The Single Most Important Variable in Fire Hazard", Fire Safety Journal, Vol. 18, No. 3, pp. 2555-272.

Peacock, R. D., Babrauskas, V. 1991, "Analysis of Large-scale Fire Test Data", Fire Safety Journal, Vol. 17, No. 5, pp. 387-414.

Quintiere, J. G. 1995, "Compartment Fire Modelling", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 3-5, National Fire Protection Association.

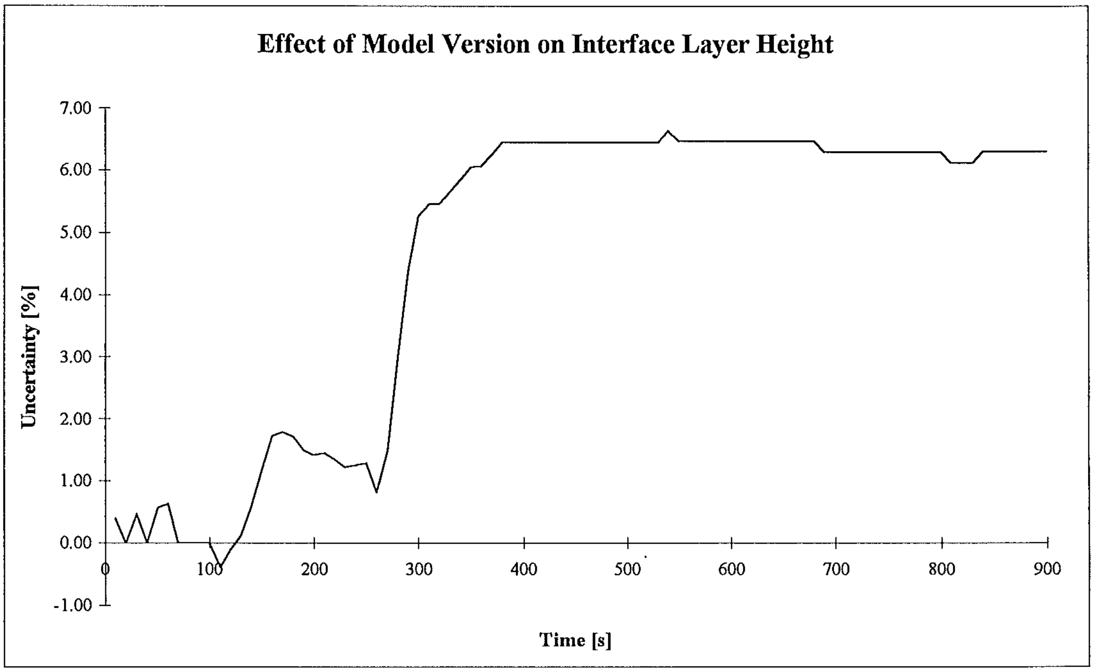
Rockett, J. A., Masahiro Morita, Cooper, L. Y. 1989, "Comparisons of NBS/Harvard VI Simulations and Data from all Runs of a Full-scale Multi-room Fire Test Model", Fire Safety Journal, Vol. 15, No. 2, pp. 115-169.

Tomovic, R., Vukobratovic, M. 1972, "General Sensitivity Theory", American Elsevier Publishing Company, Inc., 258 p.

Walton, W. D. 1995, "Zone Computer Fire Models for Enclosures", from *The SFPE Handbook of Fire Protection Engineering*, Second Edition, chapter 3-7, National Fire Protection Association, 1995.

Ziesler, P. S., Gunnerson, F. S. 1995, "Live Fire Comparisons of the CFAST Code", International Conference on Fire Research and Engineering, 10 - 15 September 1995, Orlando, Fl., pp 341-349.

Appendix A : BaseCase One Results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400
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700
800
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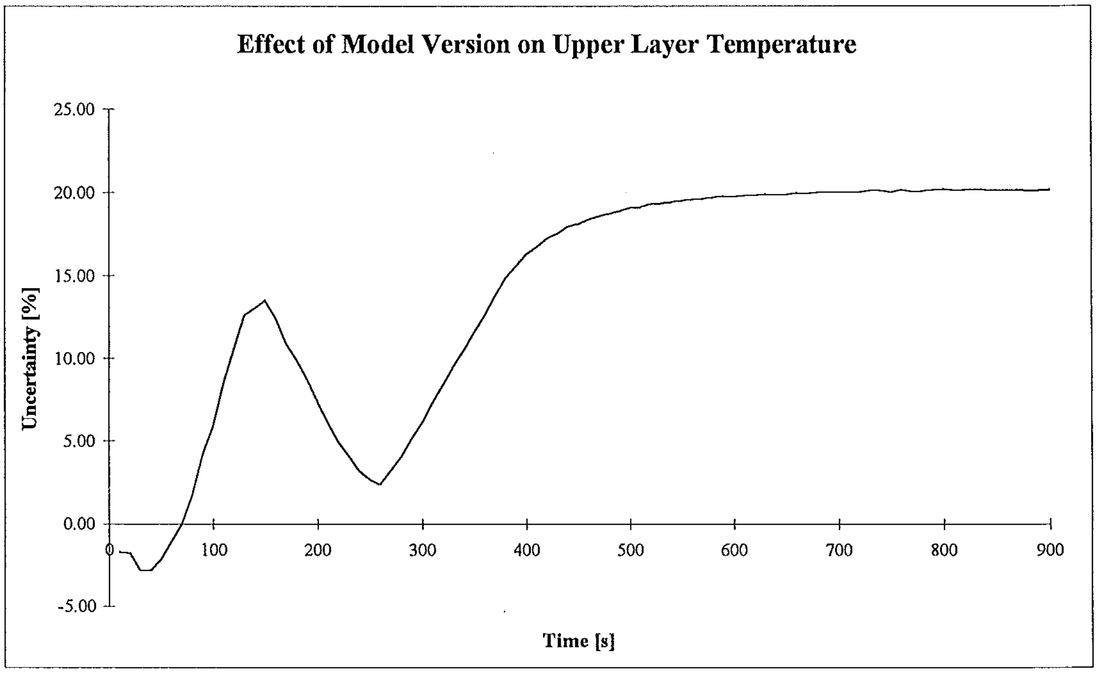
Time [s]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300
400
500
600
700
800
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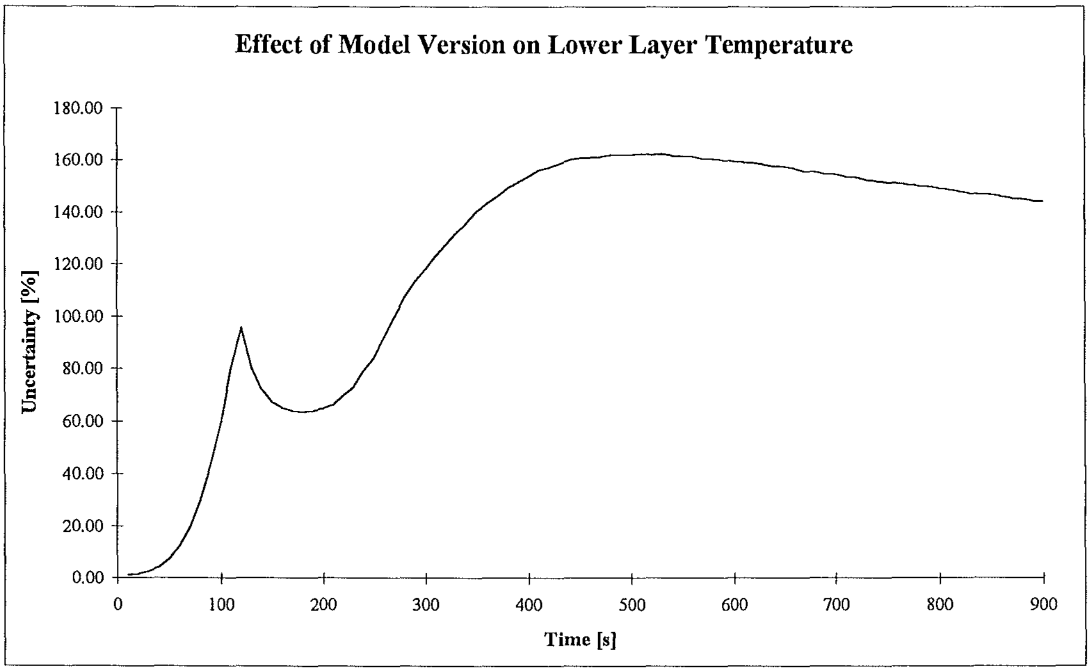
Time [s]



Effect of Model Version on Lower Layer Temperature
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100.00
80.00
60.00
40.00
20.00
0.00
Uncertainty [%]
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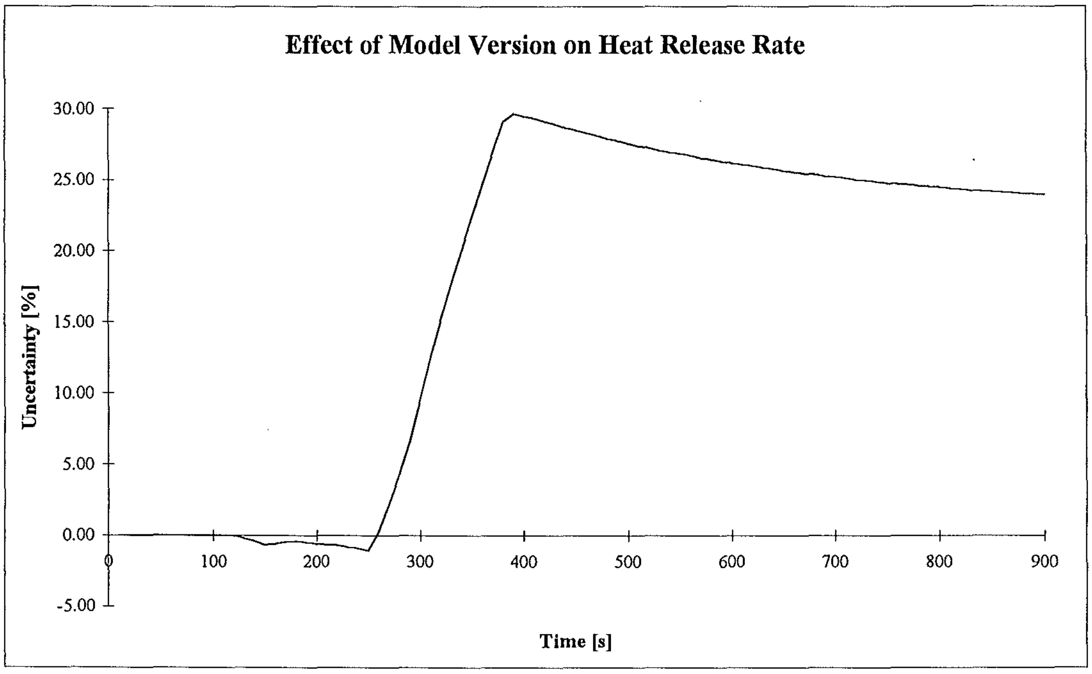
100
200
300
400
500
600
700
800
900
Time [s]



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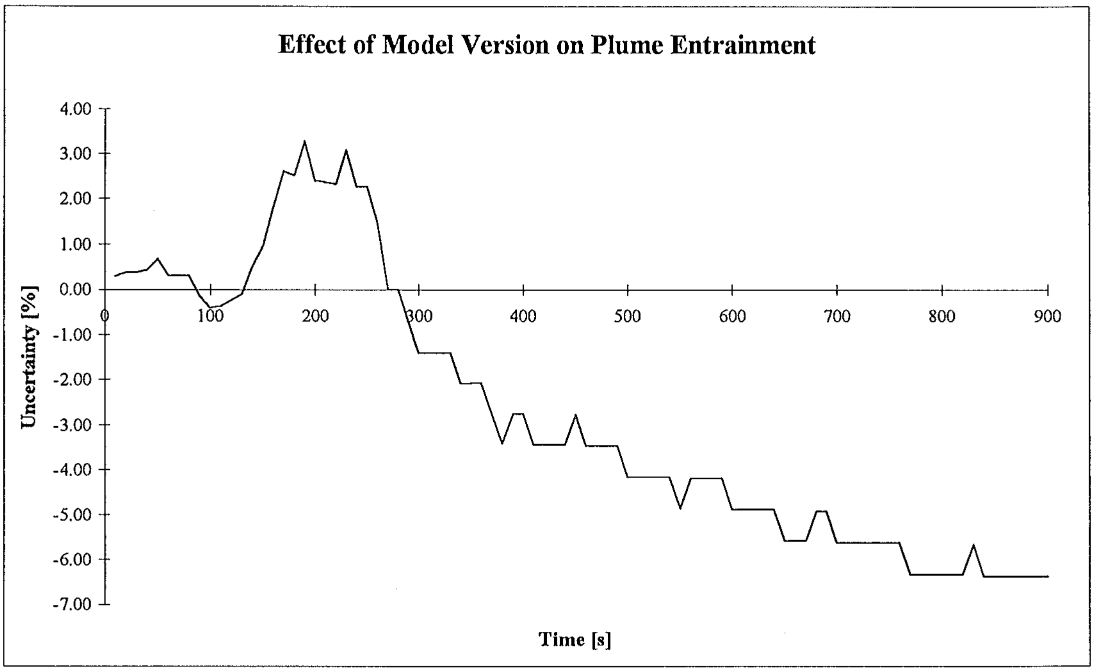
300
400
500
600
700
800
900
Time [s]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-4.00
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0
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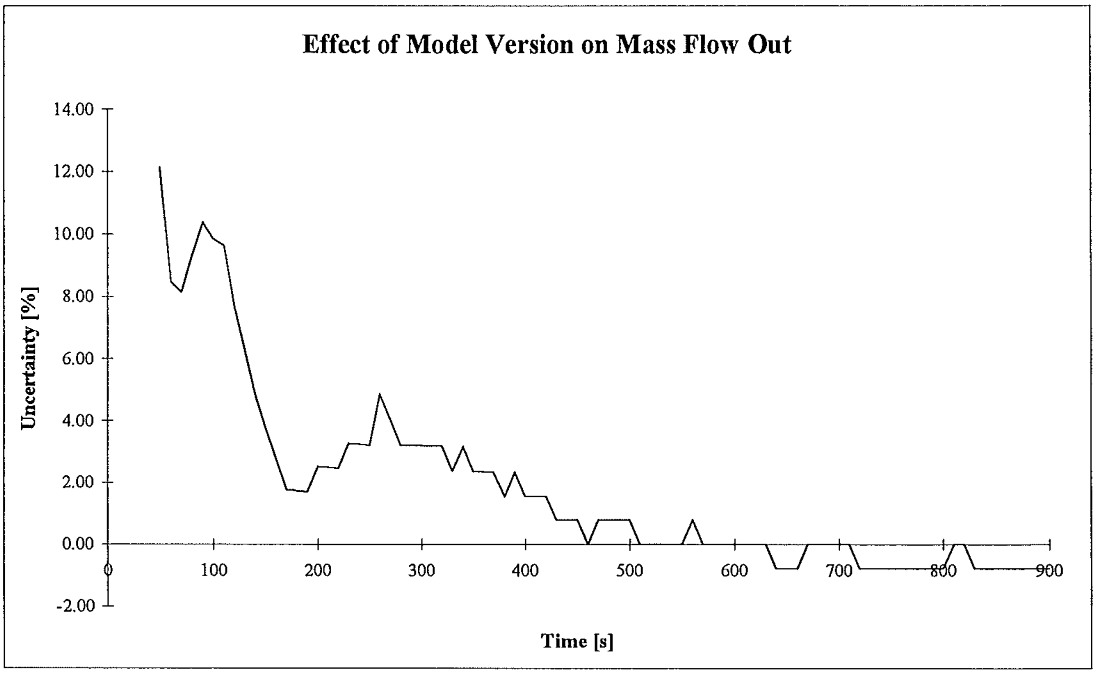
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]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400
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600
700
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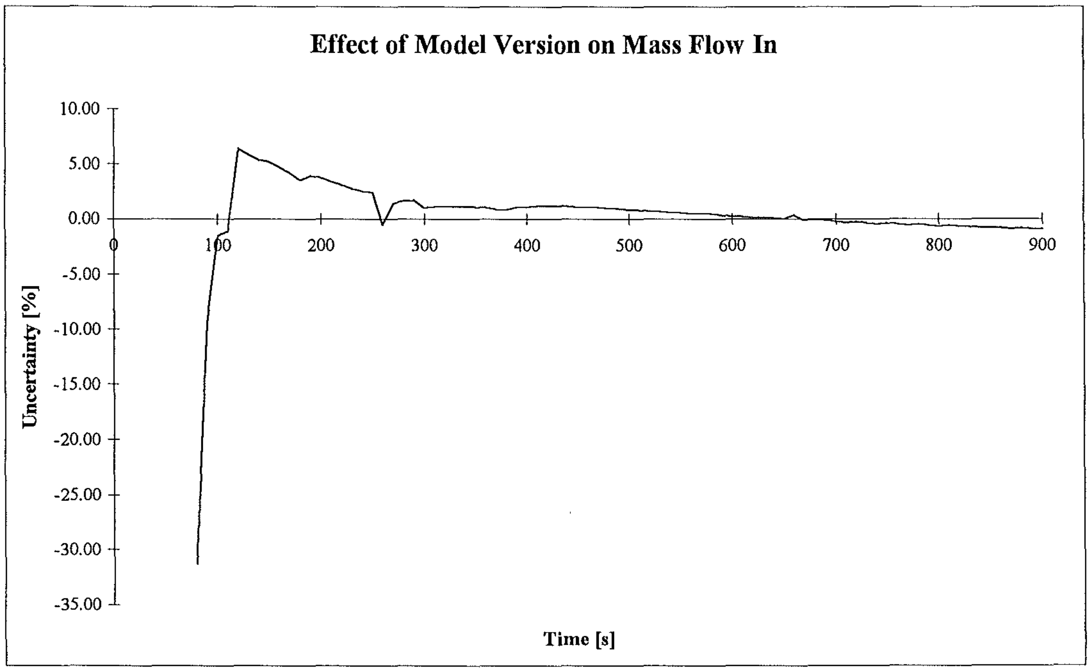
Uncertainty [%]
Time [s]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-35.00
Uncertainty [%]
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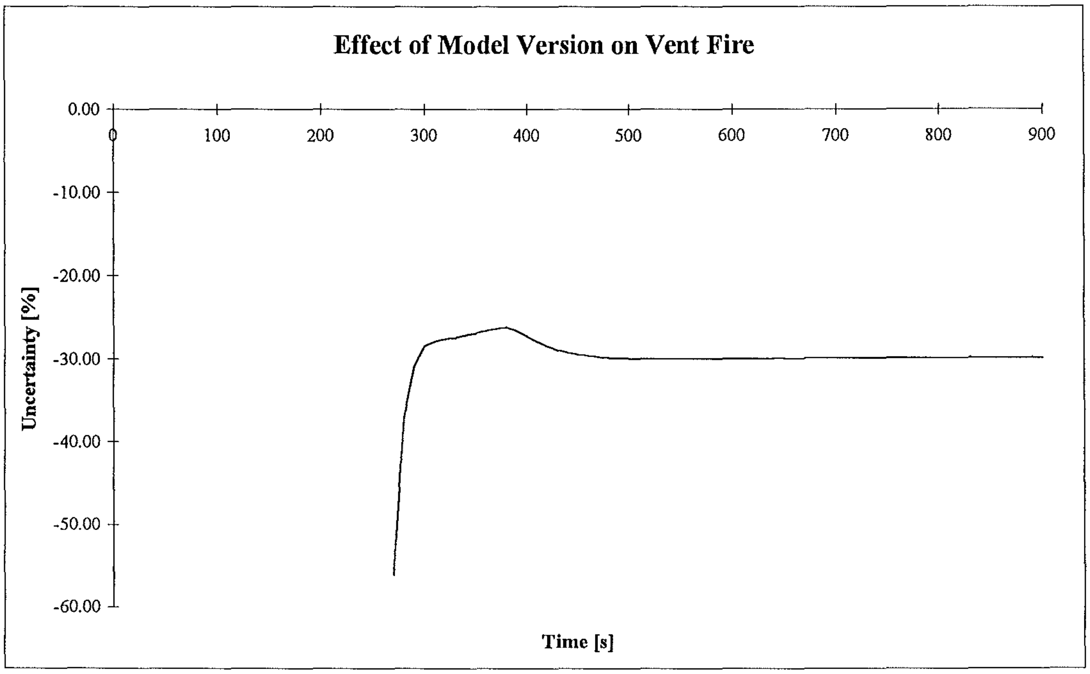
200
300
400
500
600
700
800
900
Time [s]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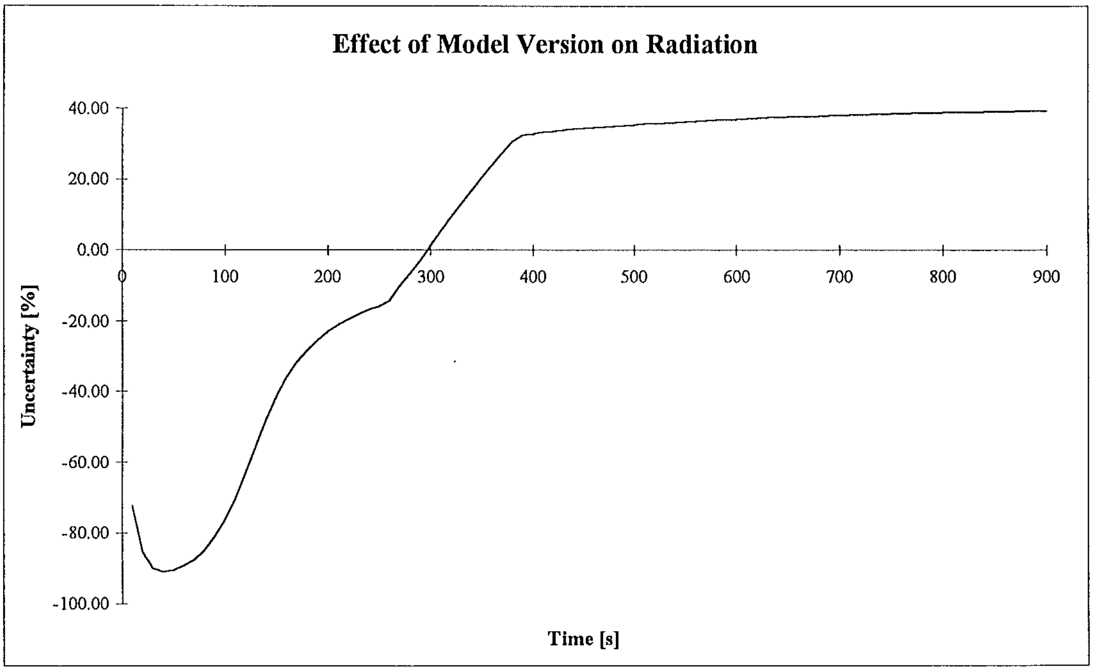
300
400
500
600
700
800
900
Time [s]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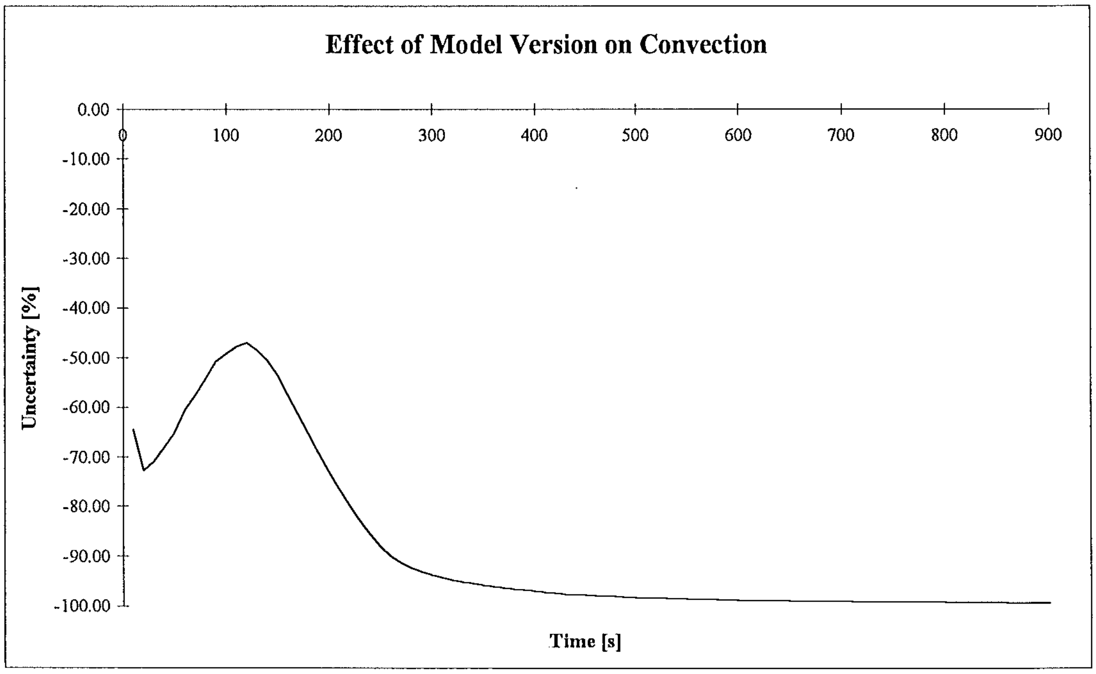
600
700
800
900
Uncertainty [%]
Time [s]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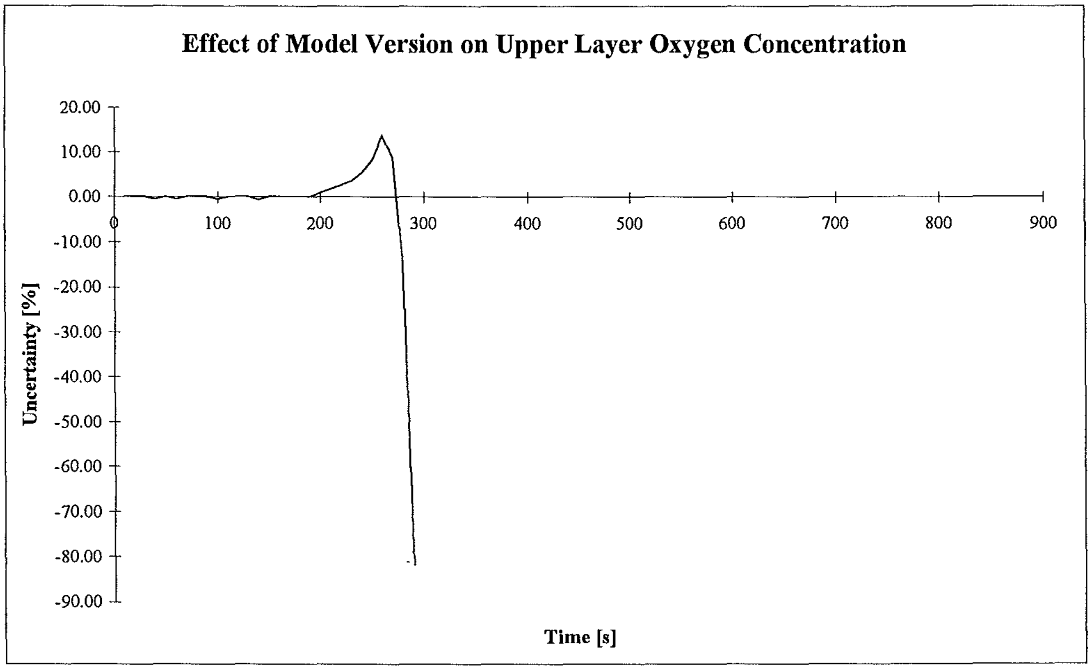
500
600
700
800
900
Uncertainty [%]
Time [s]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-60.00
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Uncertainty [%]
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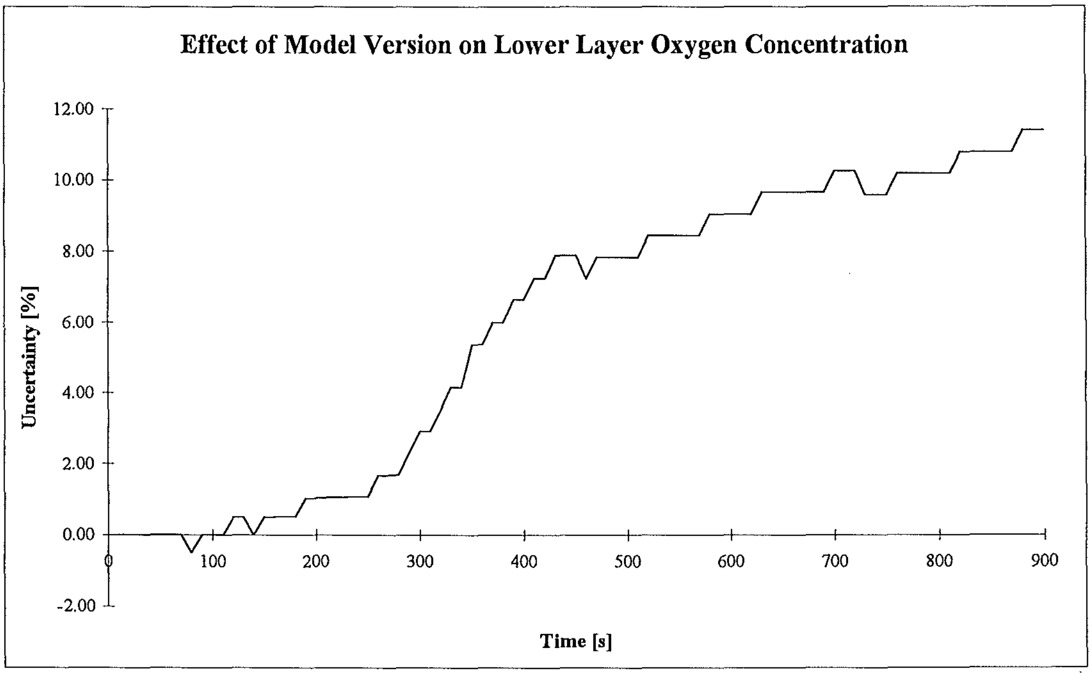
200
300
400
500
600
700
800
900
Time [s]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800
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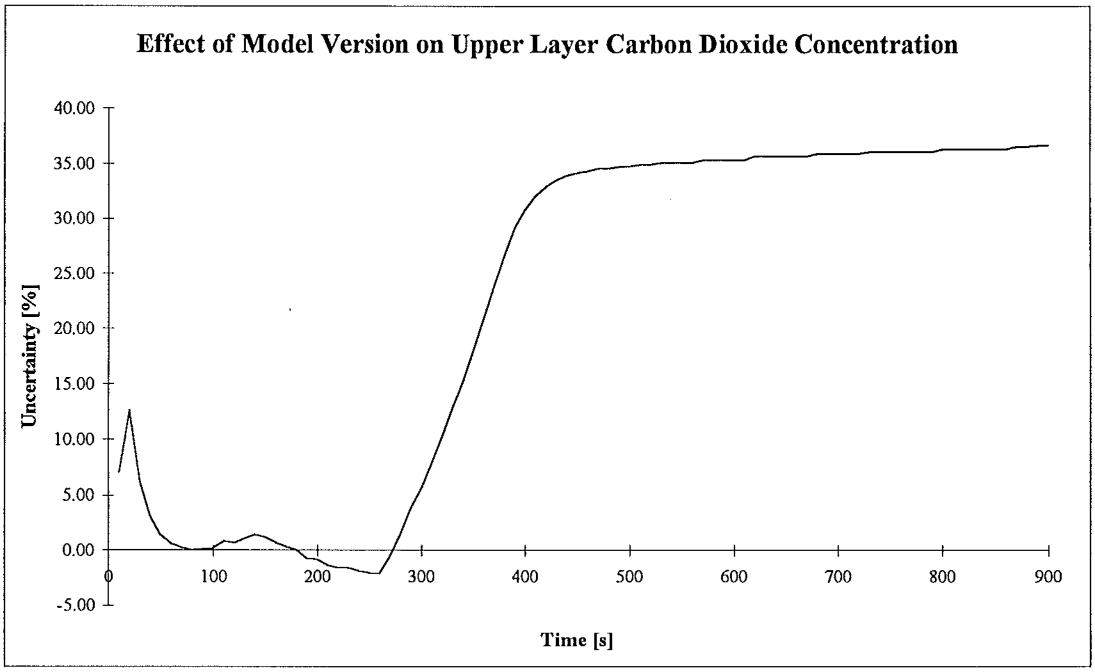
Time [s]



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30.00
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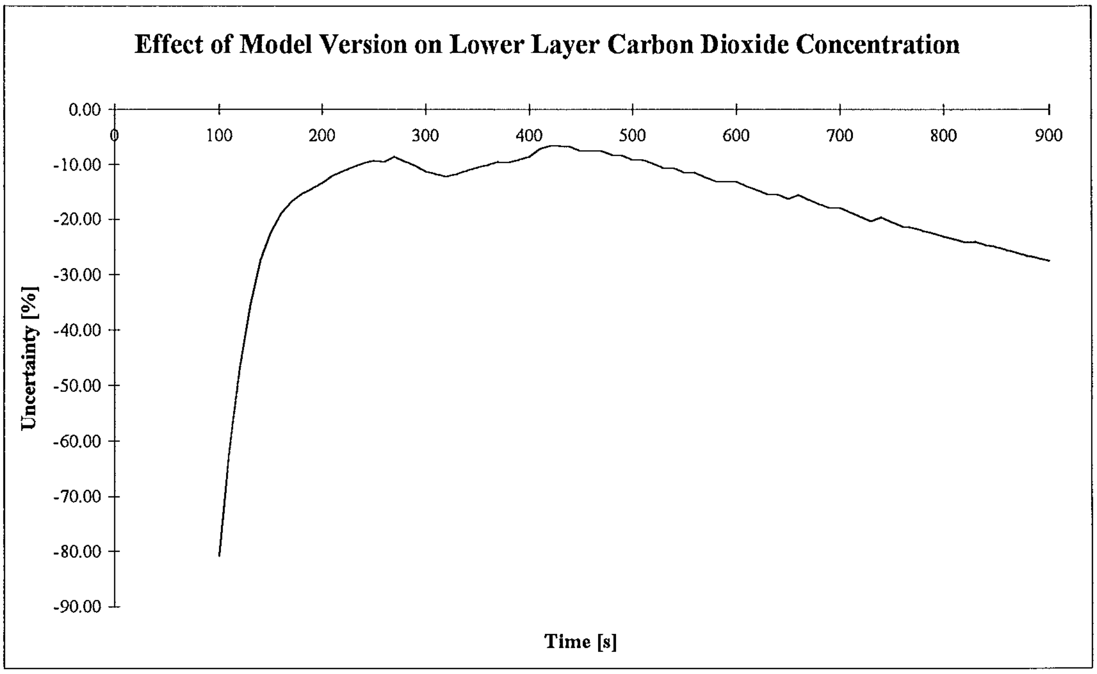
15.00
10.00
5.00
0.00
-5.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



Effect of Model Version on Lower Layer Carbon Dioxide Concentration
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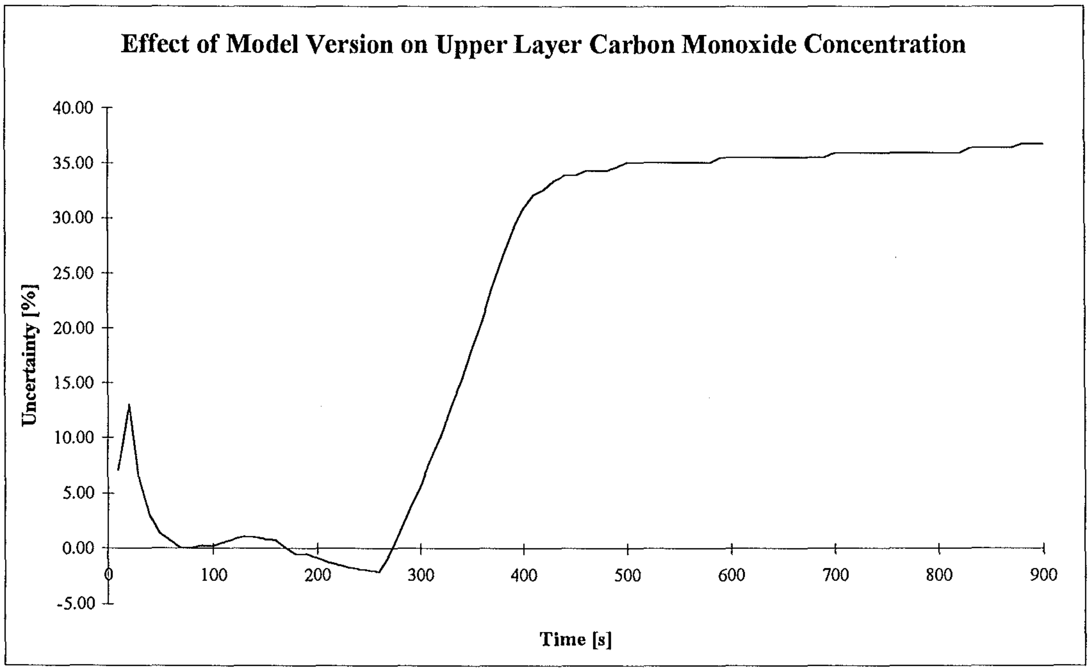
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]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Uncertainty [%]
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35.00
30.00
25.00
20.00
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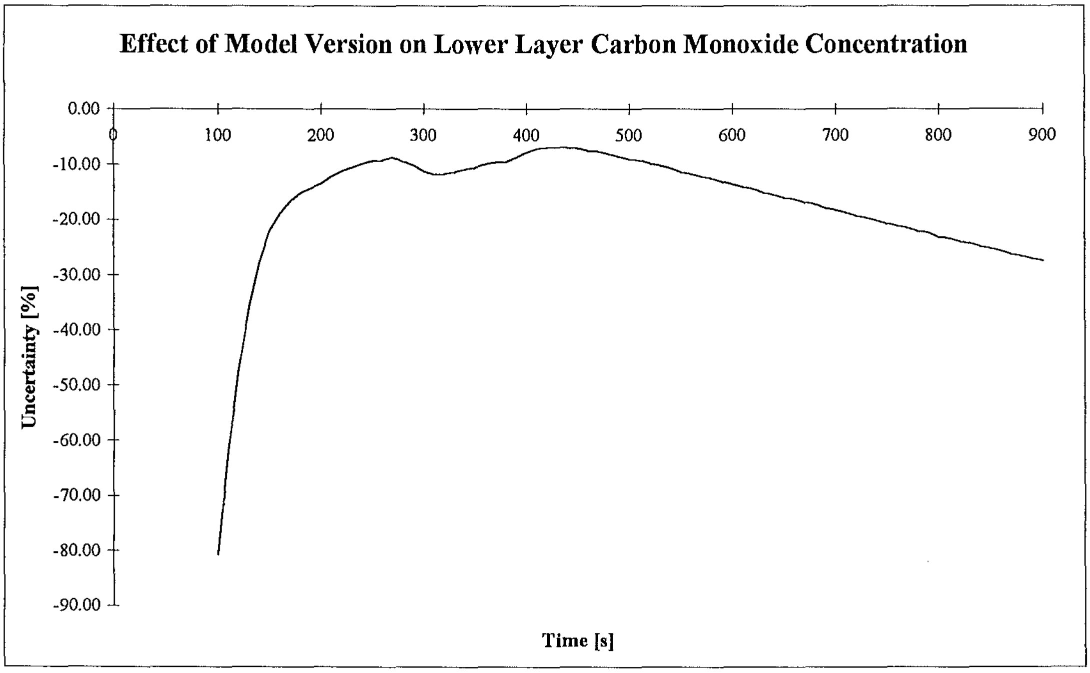
0.00
-5.00
0
100
200
300
400
500
600
700
800
900
Time [s]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Uncertainty [%]
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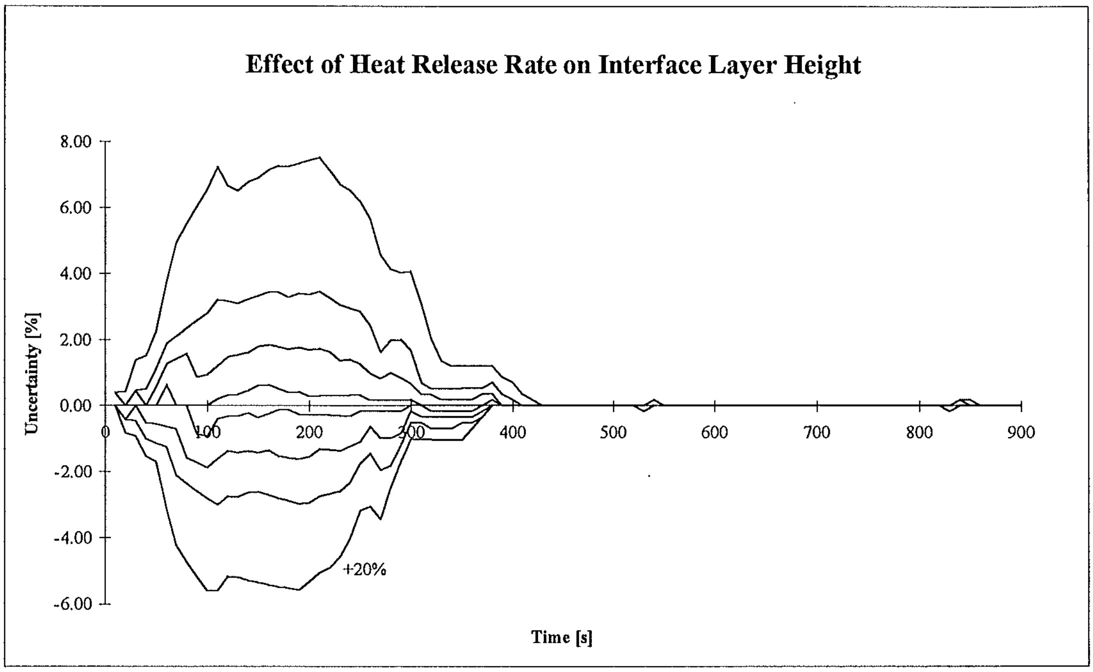
400
500
600
700
800
900
Time [s]


Effect of Heat Release Rate on Interface Layer Height
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Uncertainty [%]
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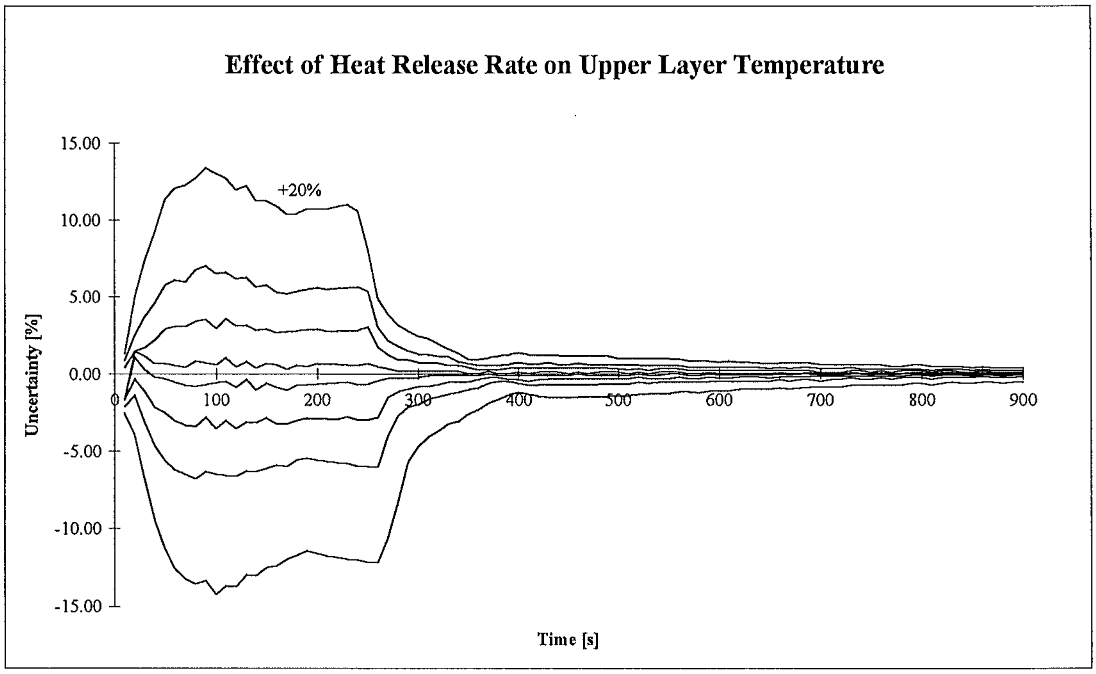
100
200
300
400
500
600
700
800
900
+20%
Time [s]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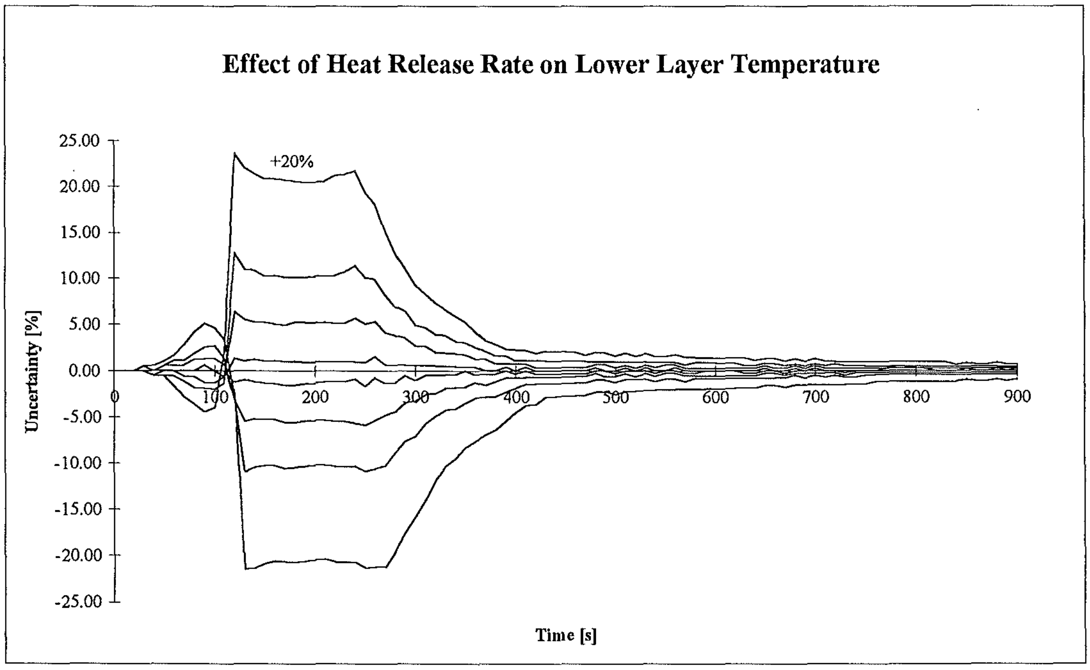
400
500
600
700
800
900
+20%
Time [s]



Effect of Heat Release Rate on Lower Layer Temperature
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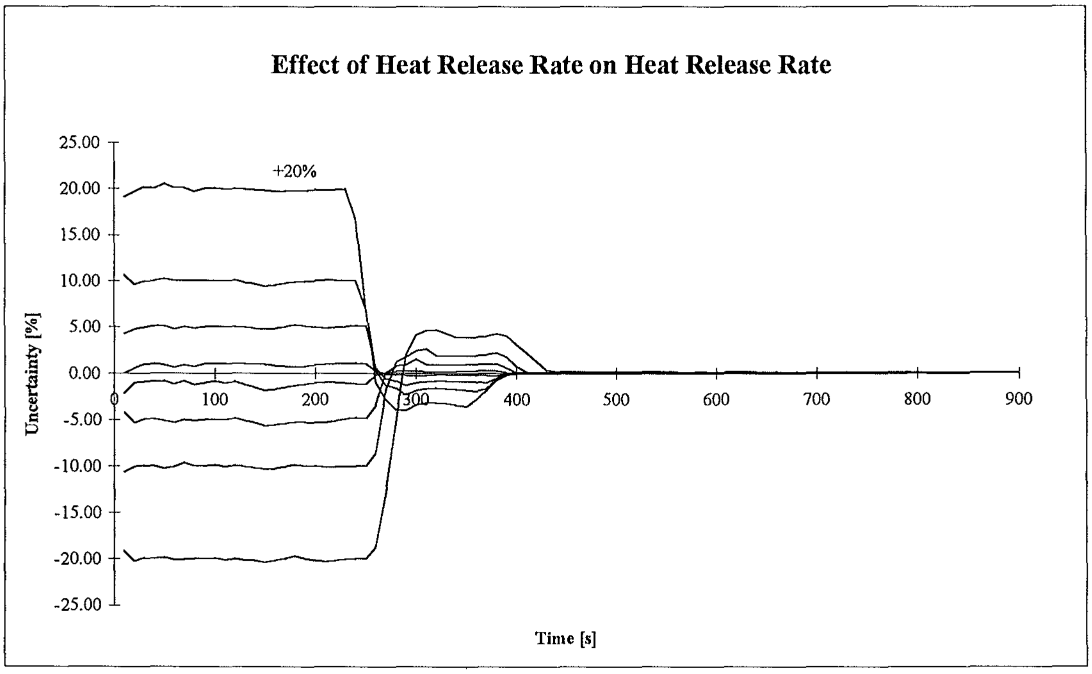
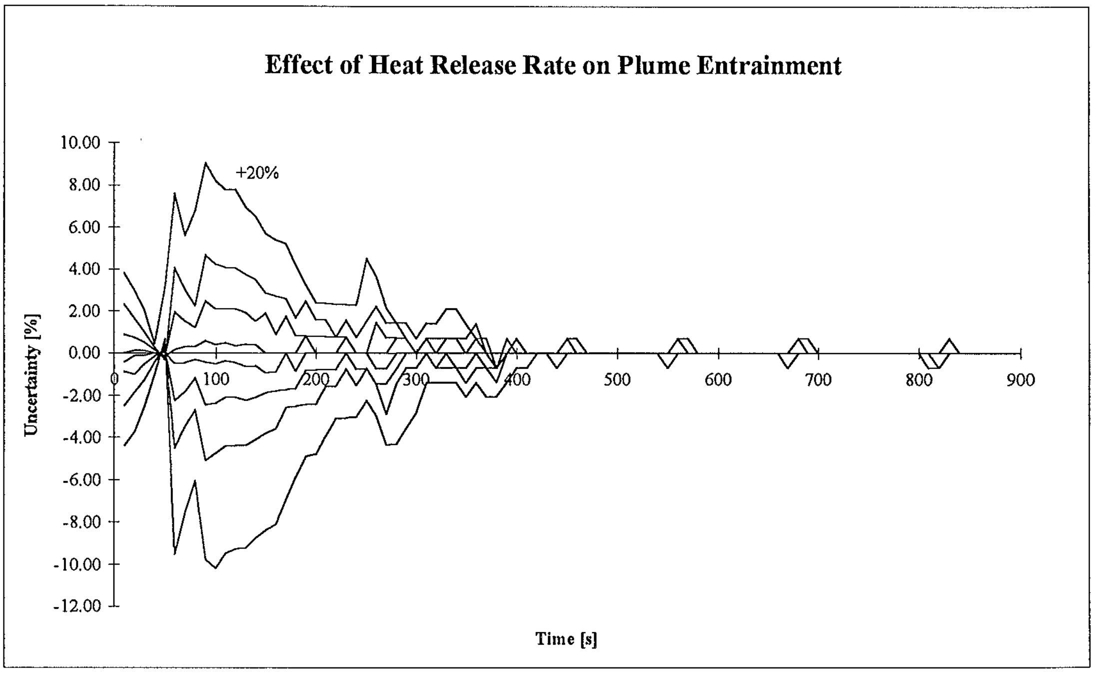
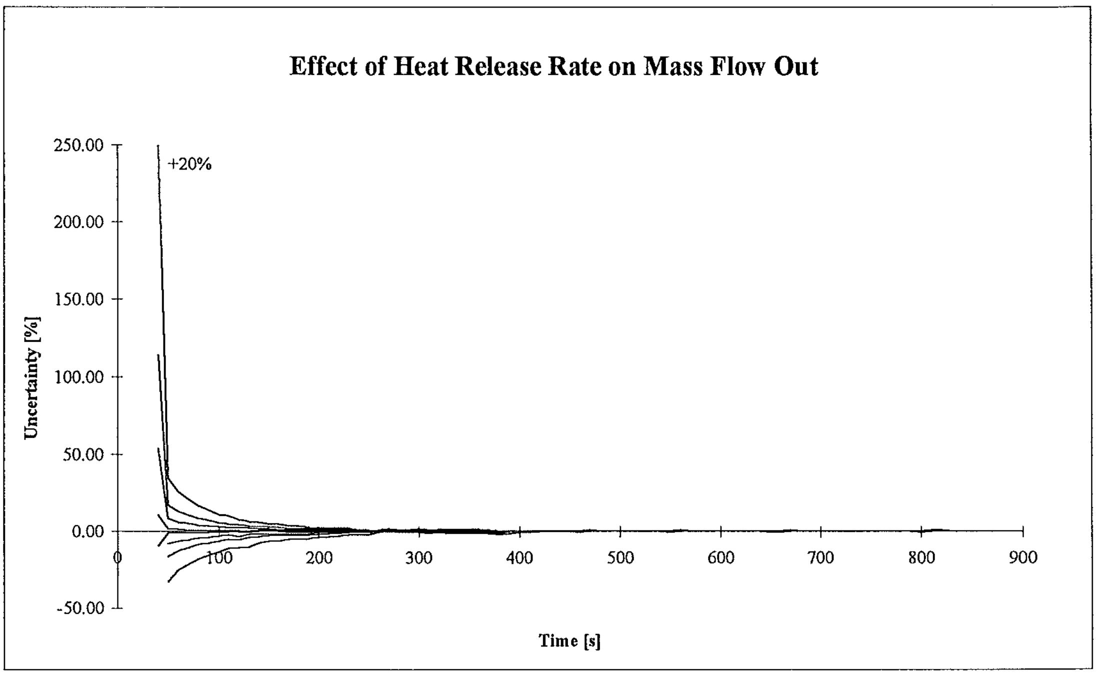
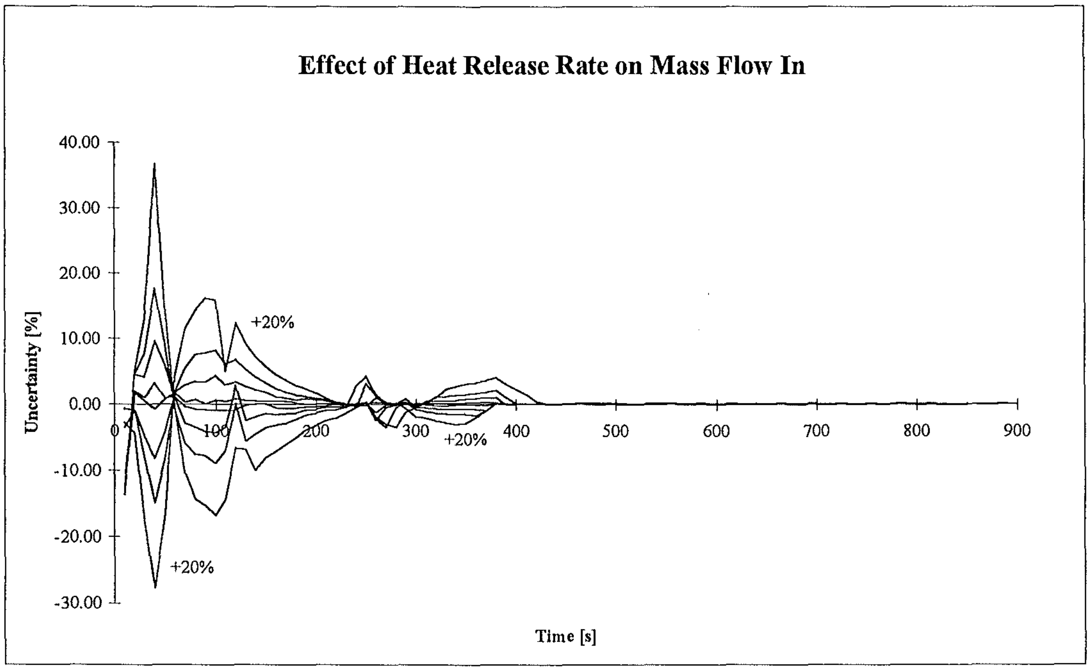
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

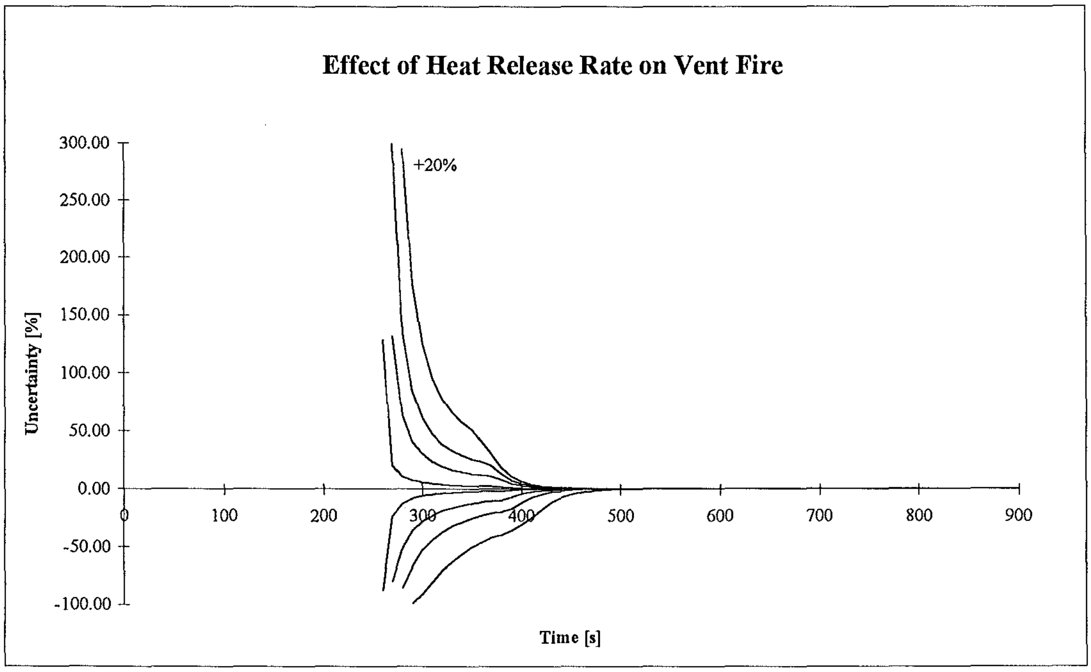


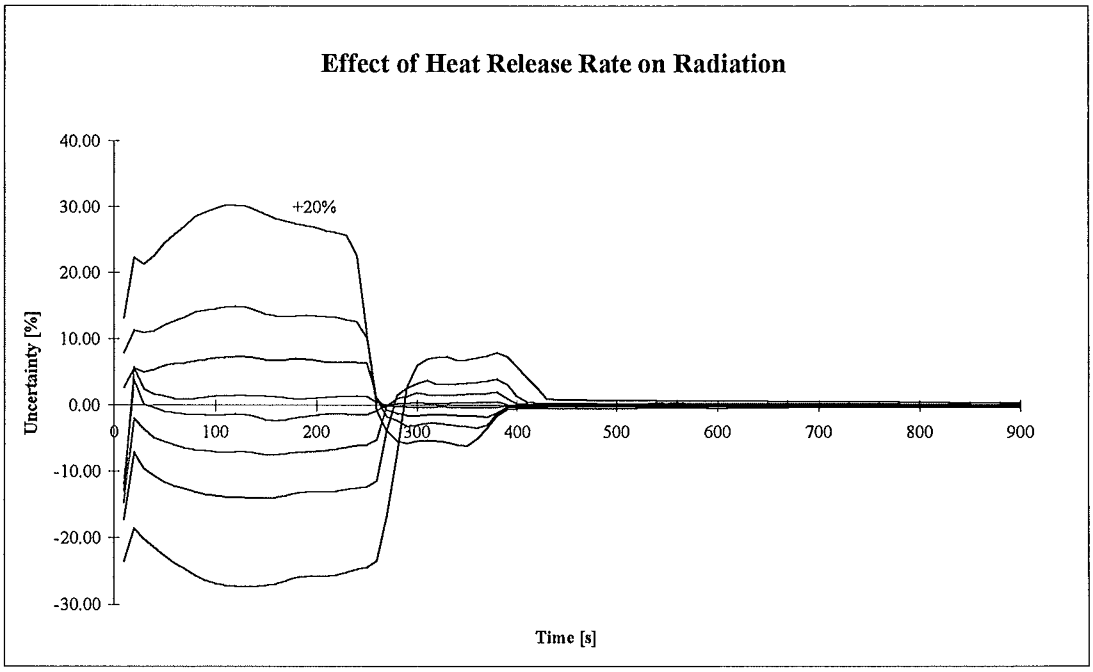
Effect of Heat Release Rate on Heat Release Rate
+20%
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Heat Release Rate on Plume Entrainment
+20%
Uncertainty [%]
Time [s]
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
0
100
200
300
400
500
600
700
800
900

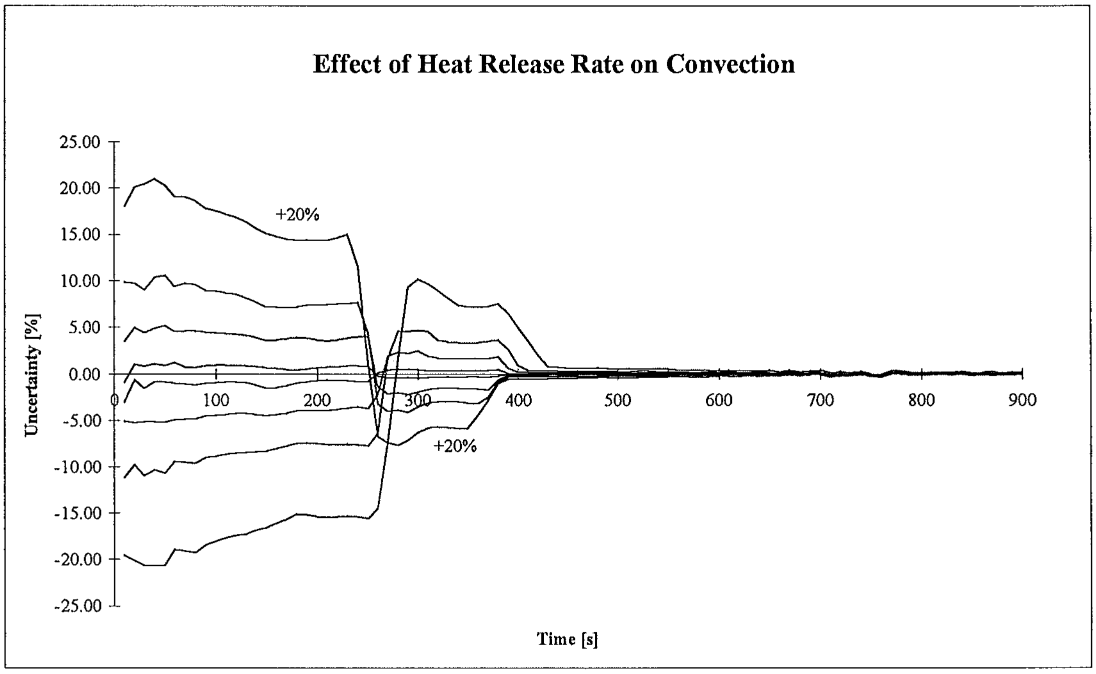

Effect of Heat Release Rate on Mass Flow Out
+20%
Uncertainty [%]
Time [s]
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
0
100
200
300
400
500
600
700
800
900


Effect of Heat Release Rate on Mass Flow In
Uncertainty [%]
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
+20%
+20%
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

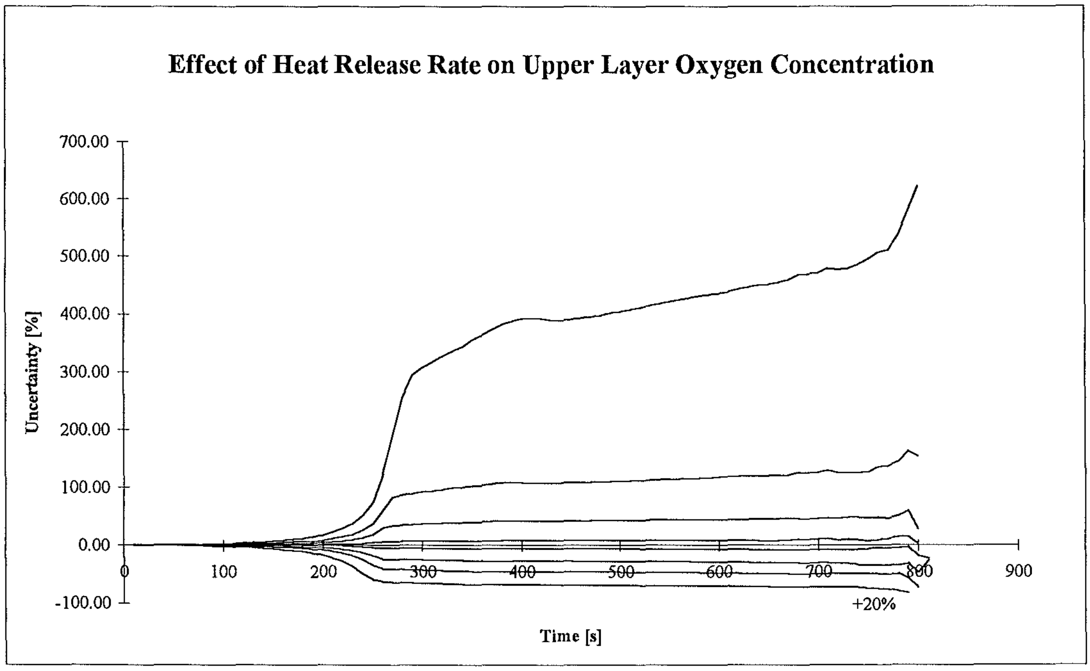

Effect of Heat Release Rate on Vent Fire
Uncertainty [%]
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

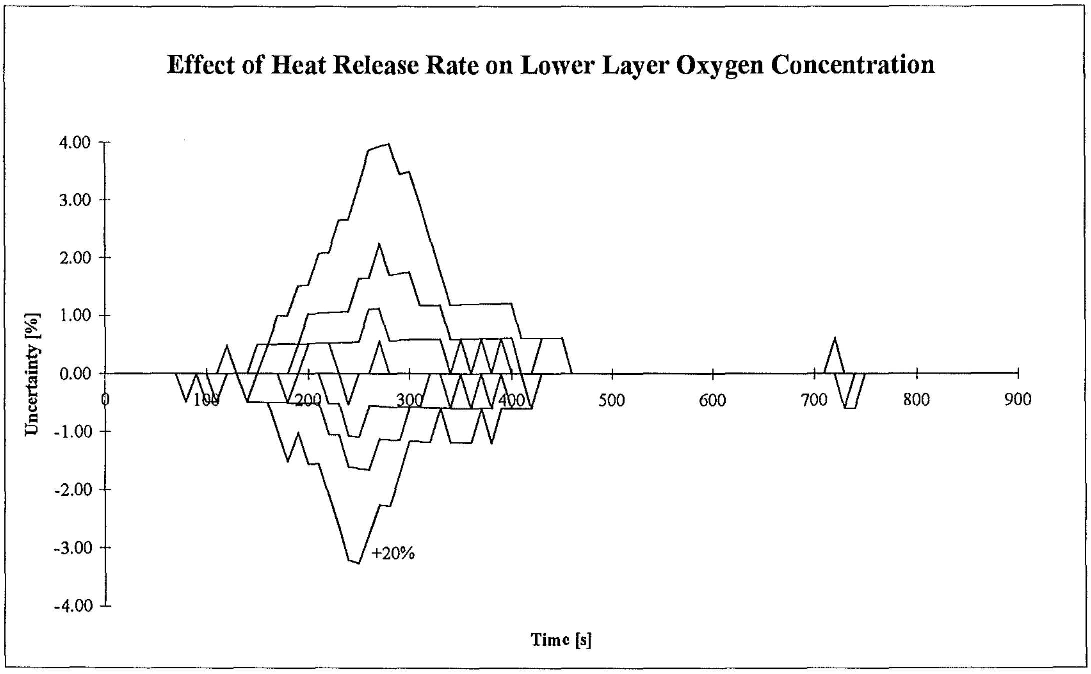


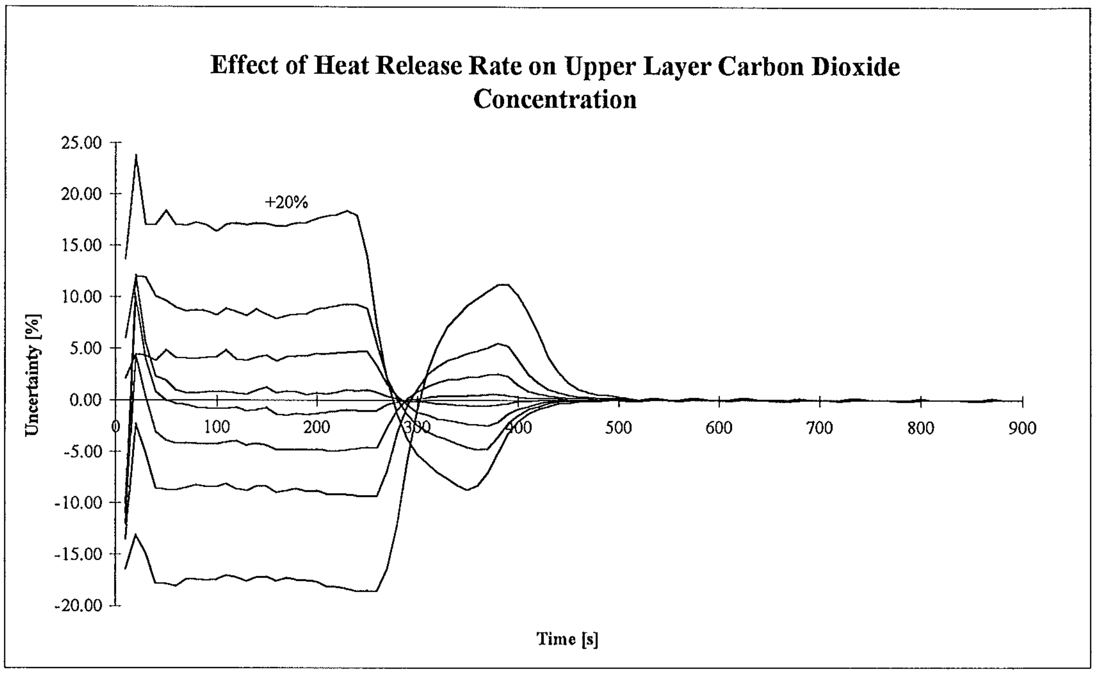
Effect of Heat Release Rate on Radiation
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

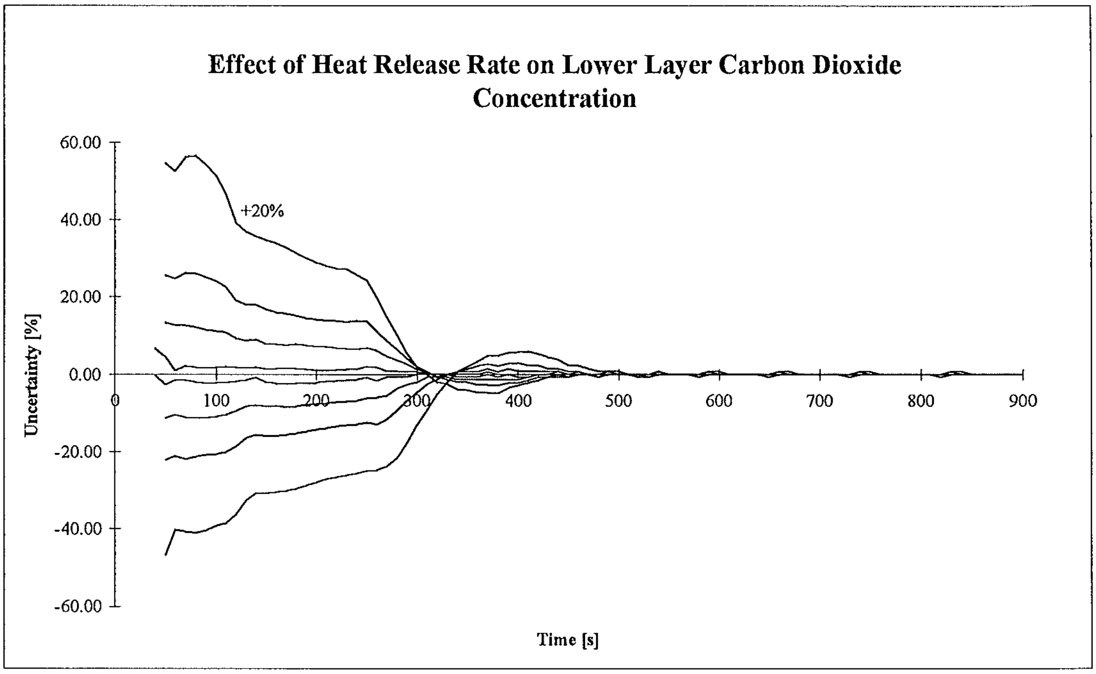


Effect of Heat Release Rate on Convection
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
+20%
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

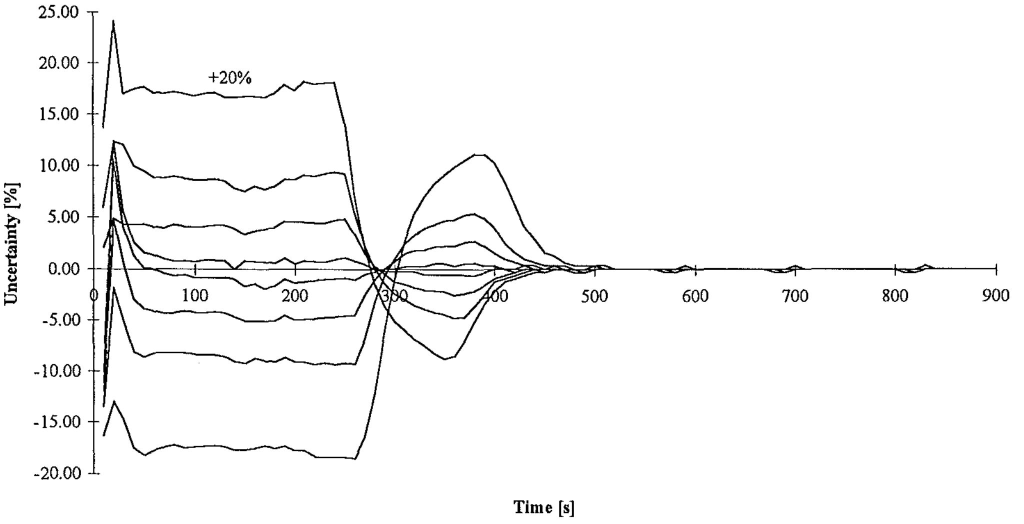

Effect of Heat Release Rate on Upper Layer Oxygen Concentration
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Heat Release Rate on Lower Layer Oxygen Concentration
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

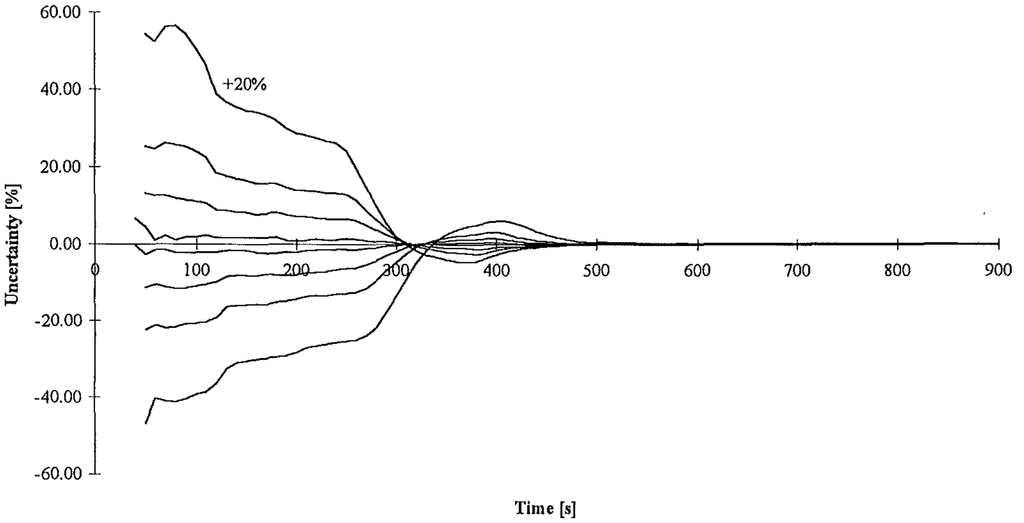

Effect of Heat Release Rate on Upper Layer Carbon Dioxide Concentration
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Heat Release Rate on Lower Layer Carbon Dioxide Concentration
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

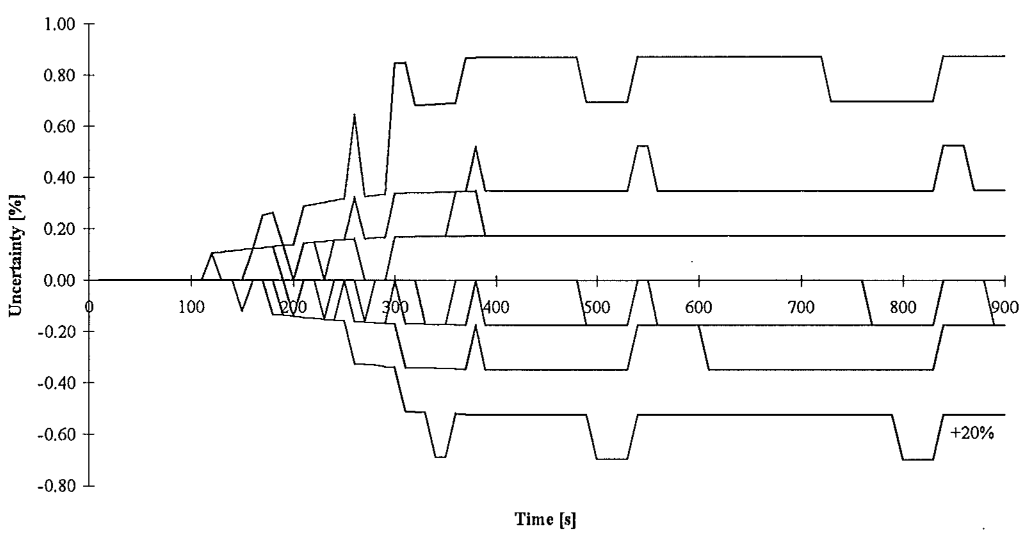
Effect of Heat Release Rate on Upper Layer Carbon Monoxide Concentration



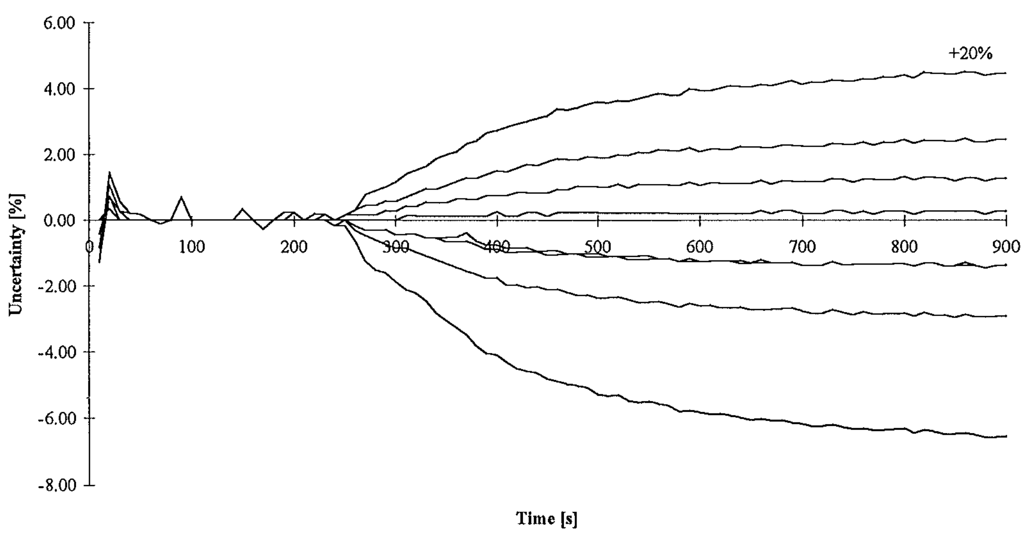
Effect of Heat Release Rate on Lower Layer Carbon Monoxide Concentration

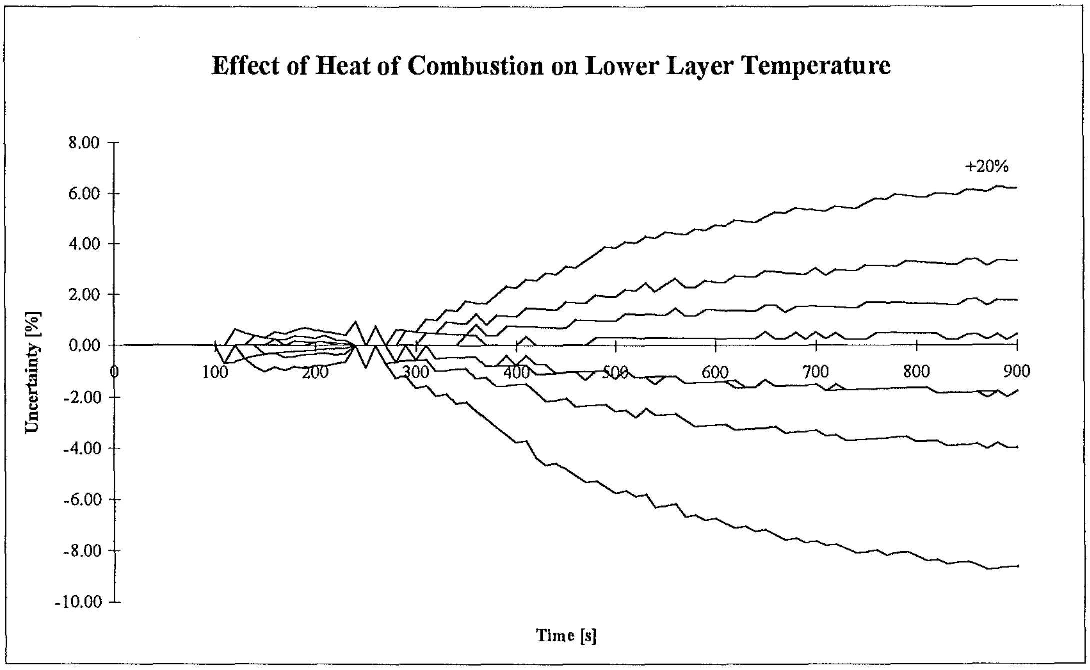


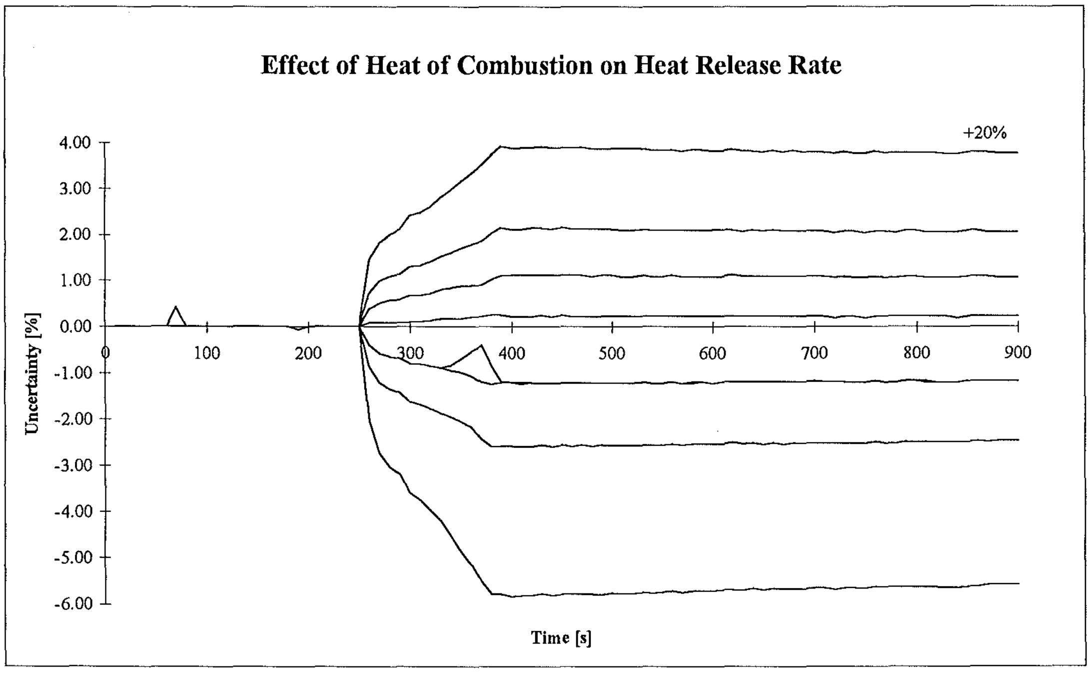
Effect of Heat of Combustion on Interface Layer Height

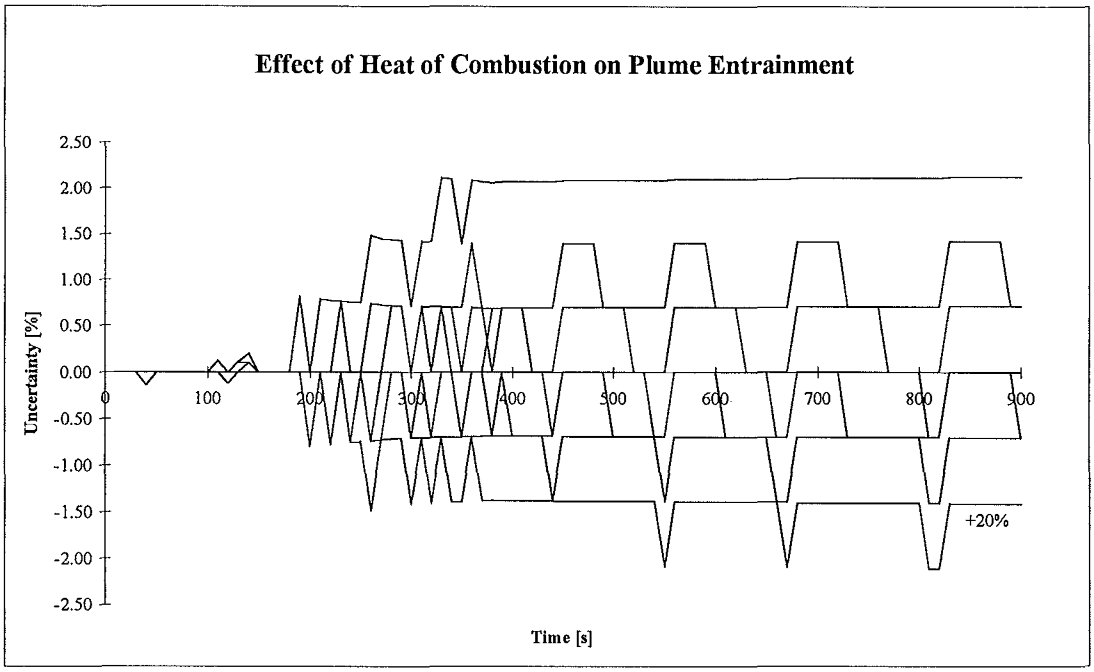


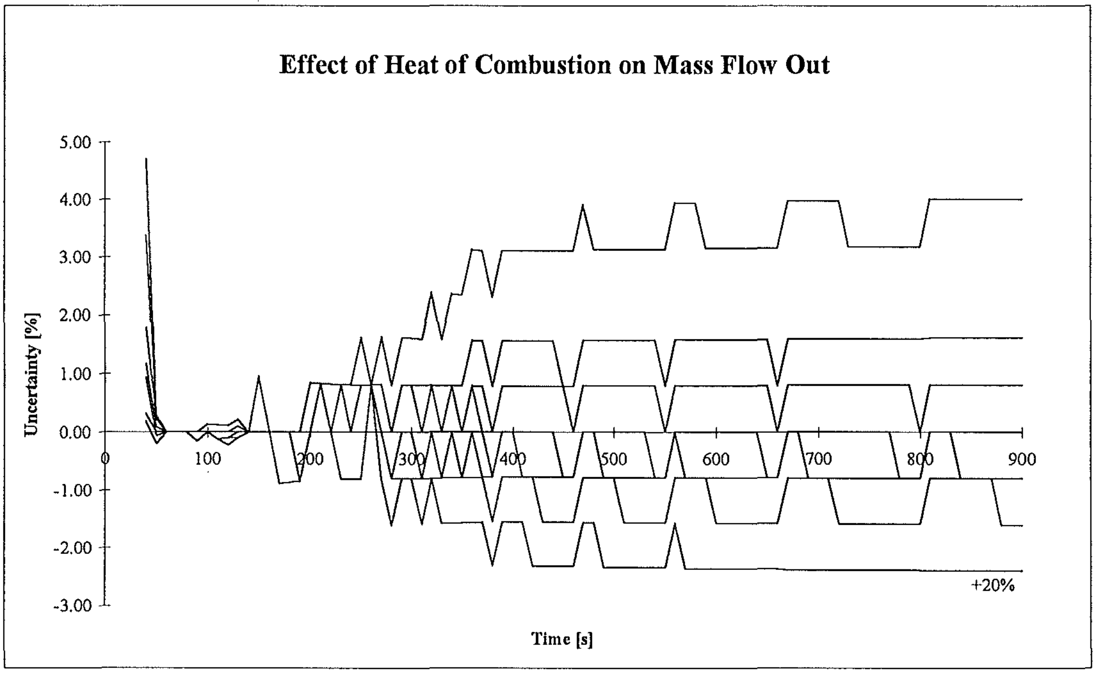
Effect of Heat of Combustion on Upper Layer Temperature

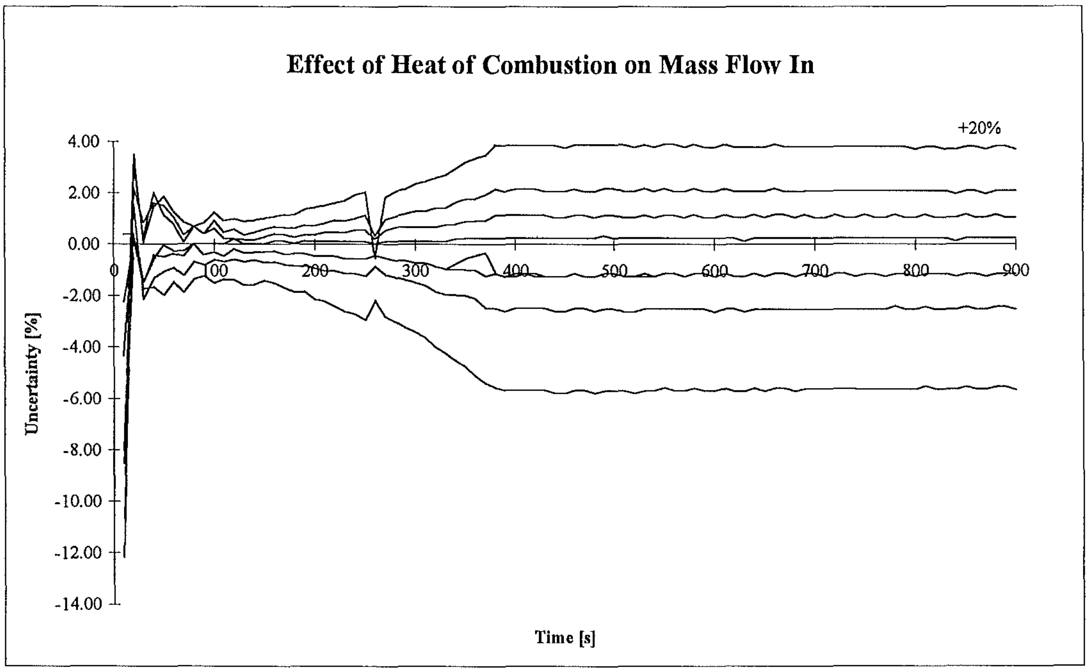


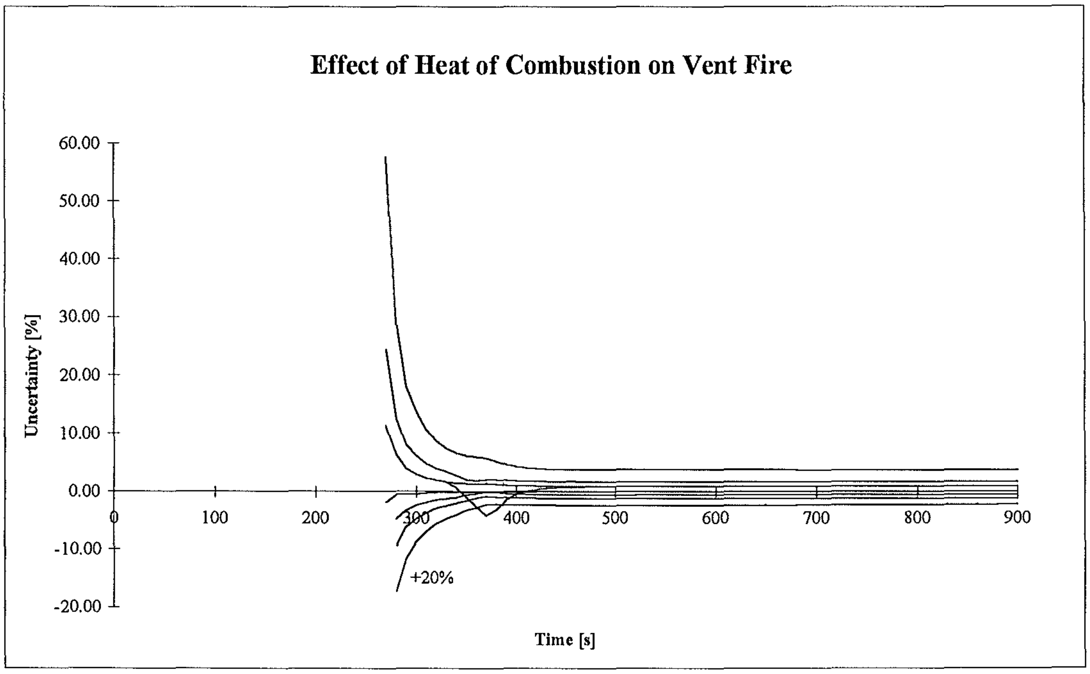

Effect of Heat of Combustion on Lower Layer Temperature
+20%
Uncertainty [%]
Time [s]

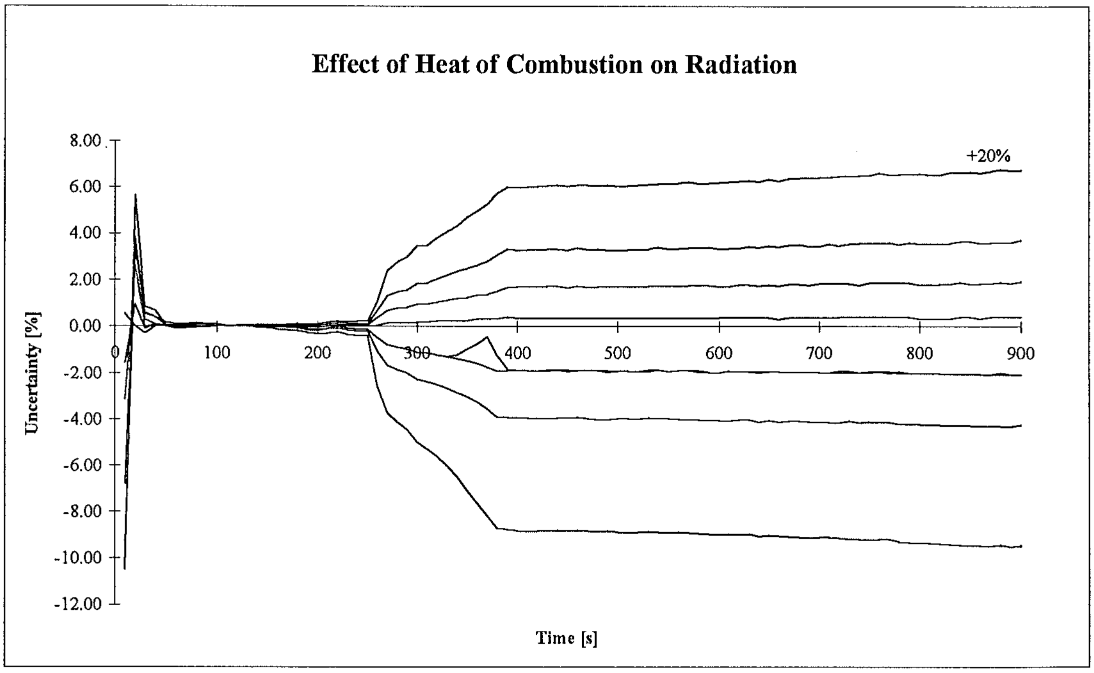

Effect of Heat of Combustion on Heat Release Rate
+20%
Uncertainty [%]
Time [s]


Effect of Heat of Combustion on Plume Entrainment
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

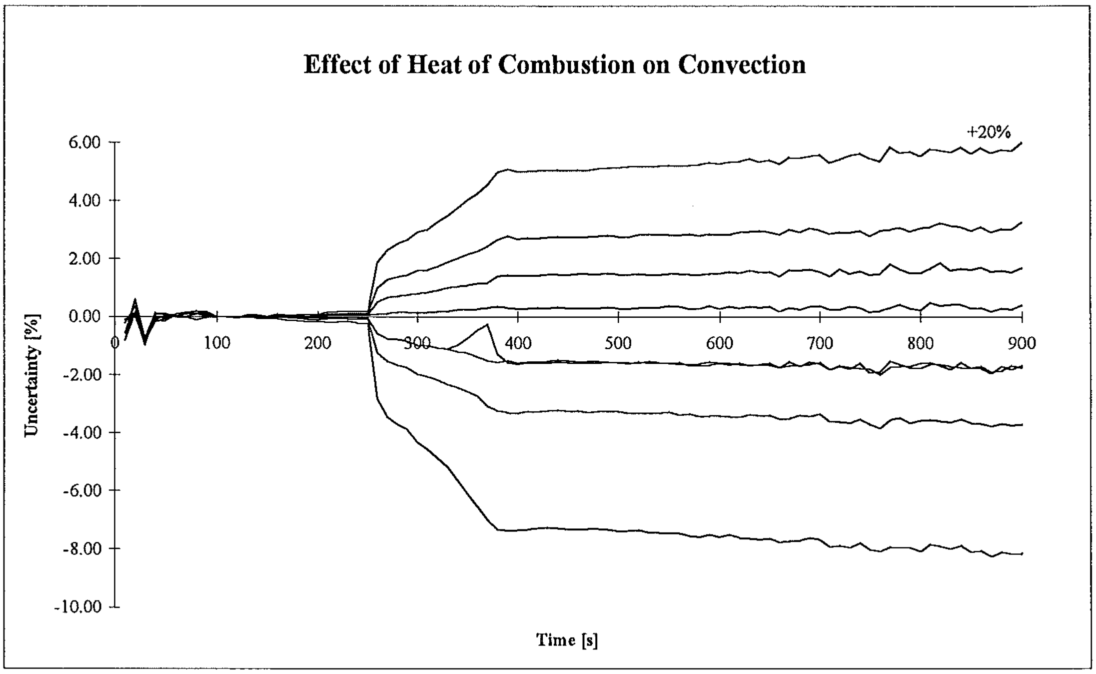

Effect of Heat of Combustion on Mass Flow Out
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Heat of Combustion on Mass Flow In
+20%
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

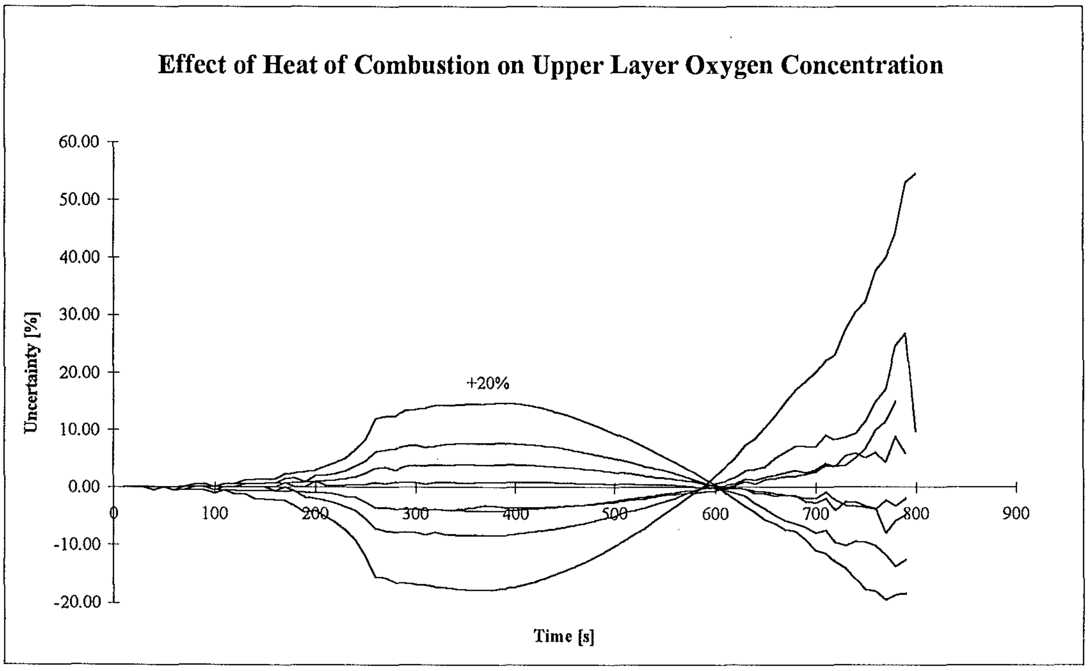

Effect of Heat of Combustion on Vent Fire
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

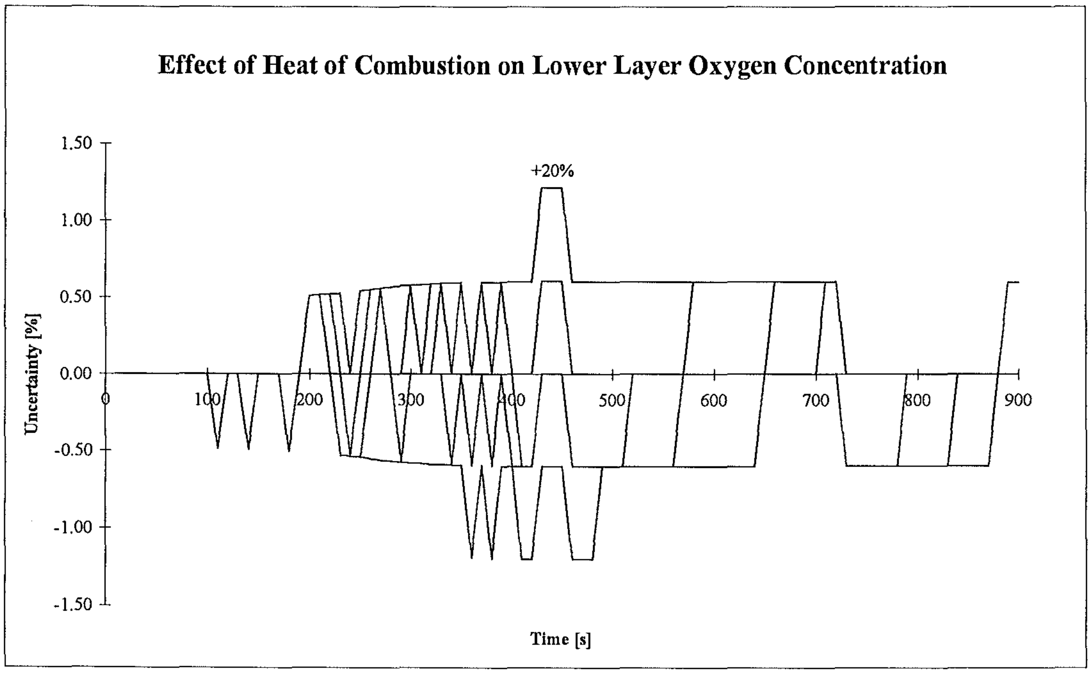


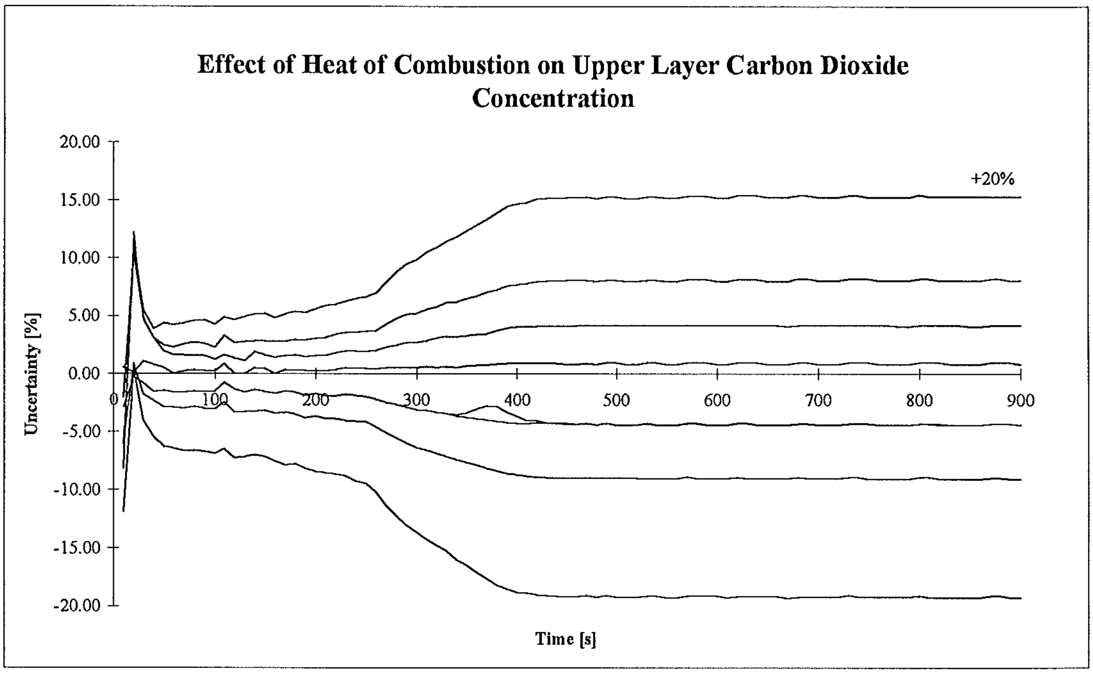
Effect of Heat of Combustion on Radiation
+20%
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]

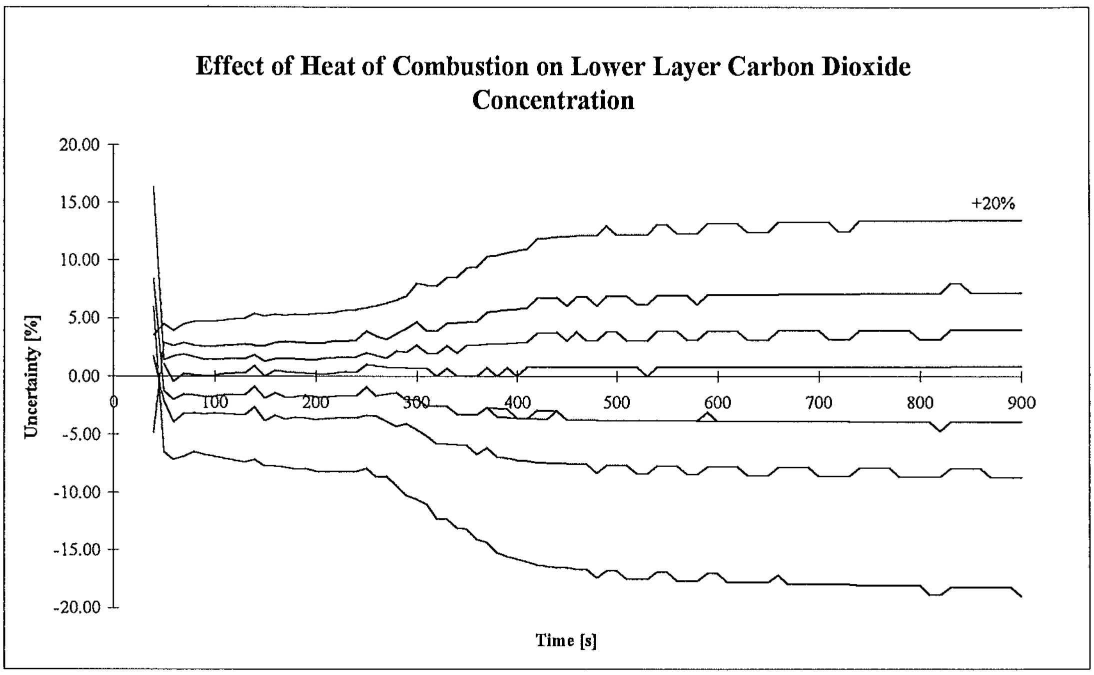


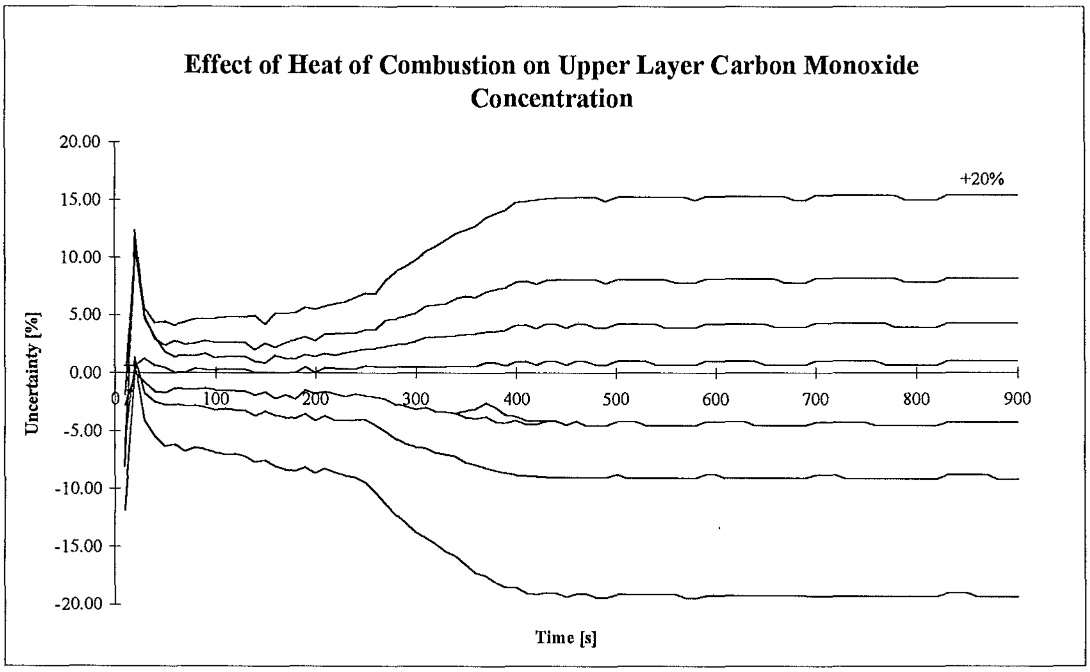
Effect of Heat of Combustion on Convection
+20%
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]

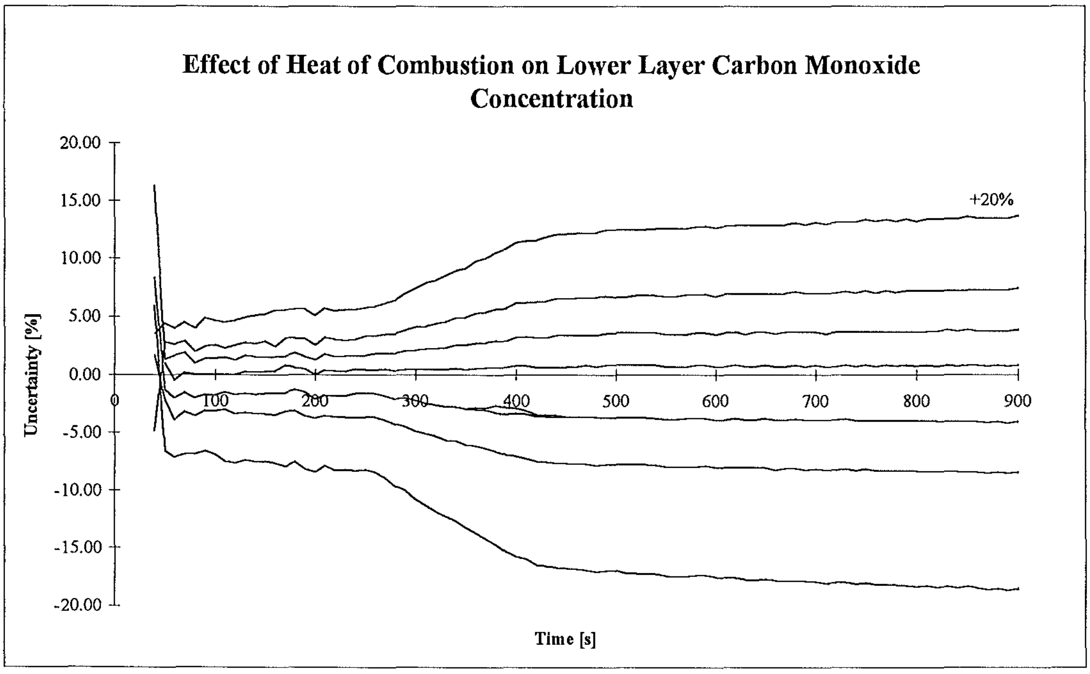

Effect of Heat of Combustion on Upper Layer Oxygen Concentration
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

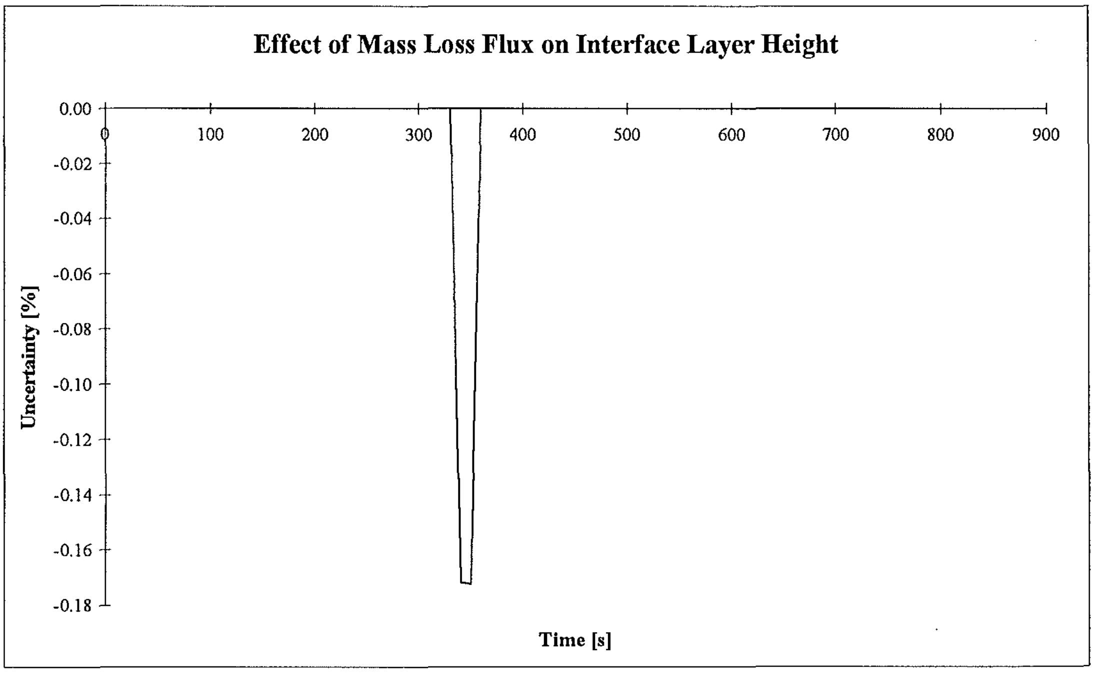

Effect of Heat of Combustion on Lower Layer Oxygen Concentration
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

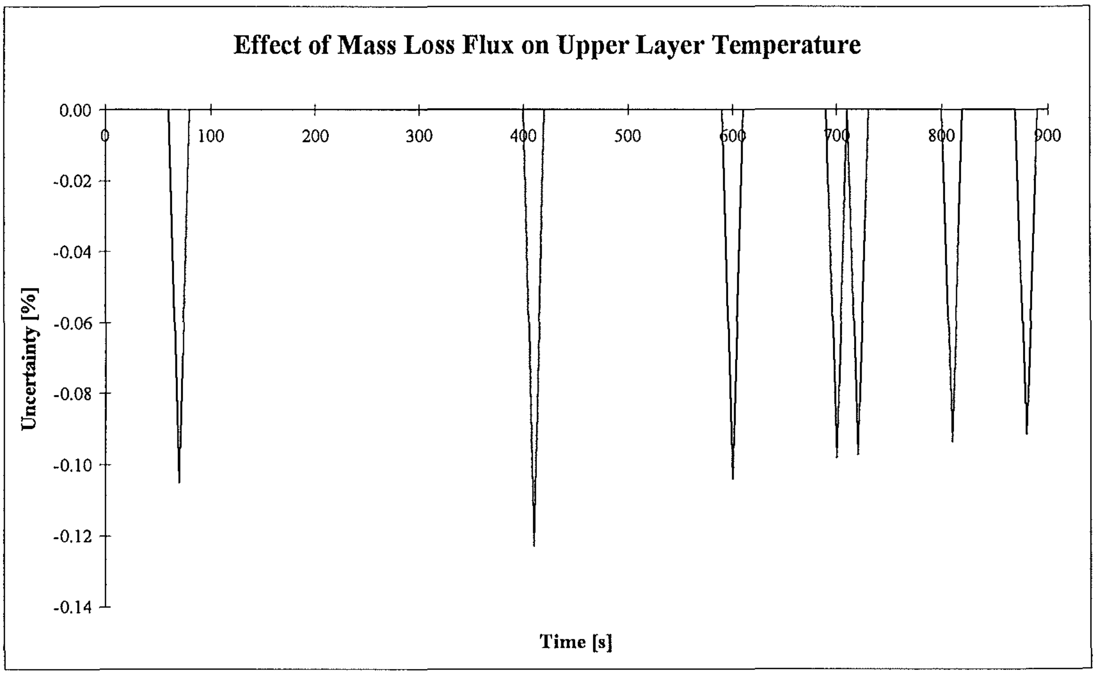

Effect of Heat of Combustion on Upper Layer Carbon Dioxide Concentration
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

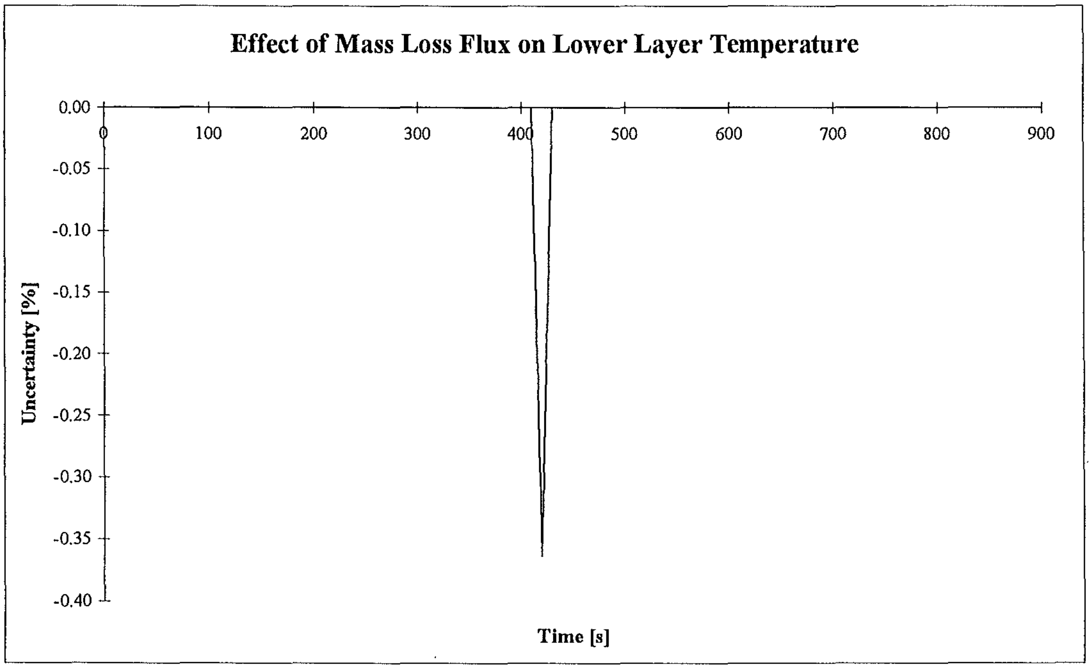

Effect of Heat of Combustion on Lower Layer Carbon Dioxide Concentration
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

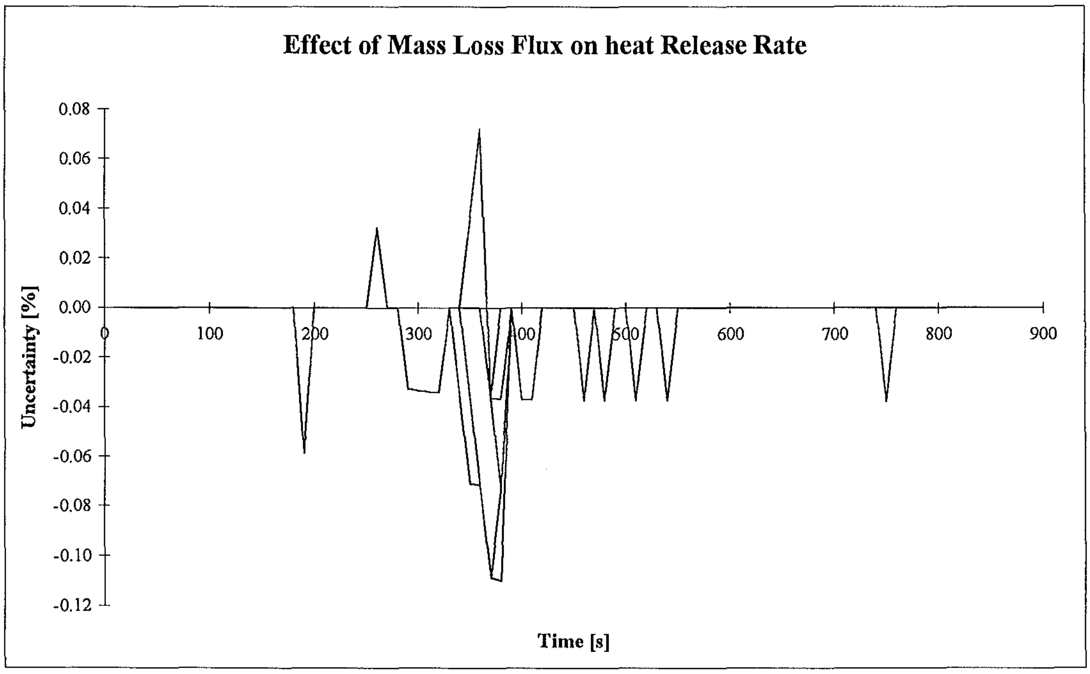

Effect of Heat of Combustion on Upper Layer Carbon Monoxide Concentration
+20%
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

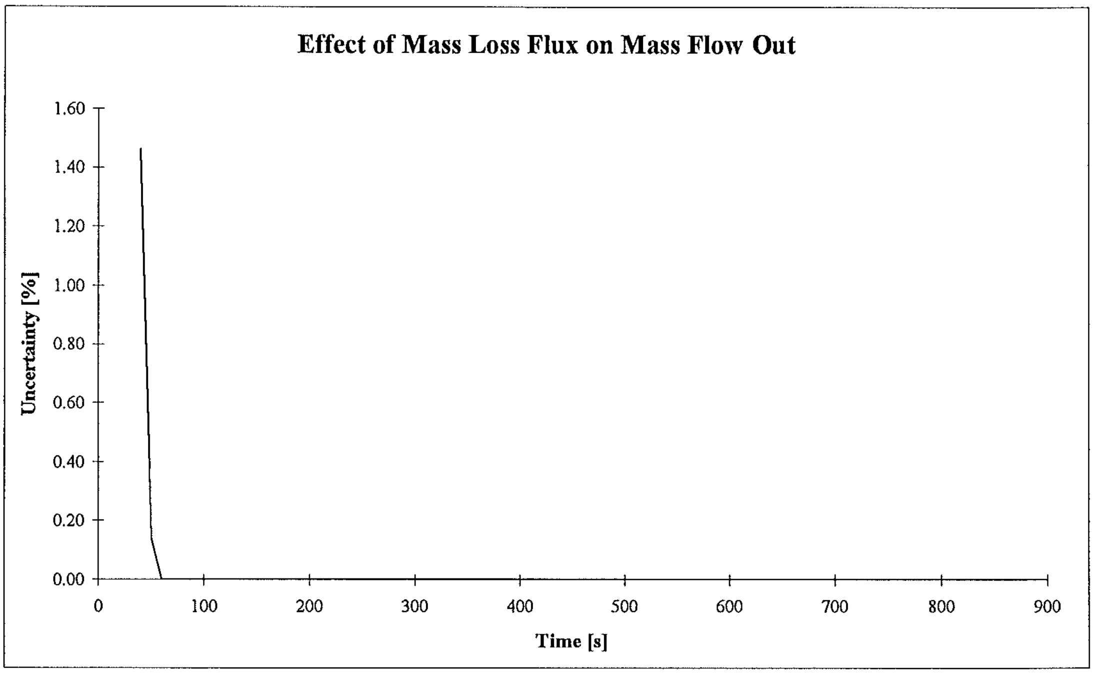

Effect of Heat of Combustion on Lower Layer Carbon Monoxide Concentration
+20%
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Mass Loss Flux on Interface Layer Height
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

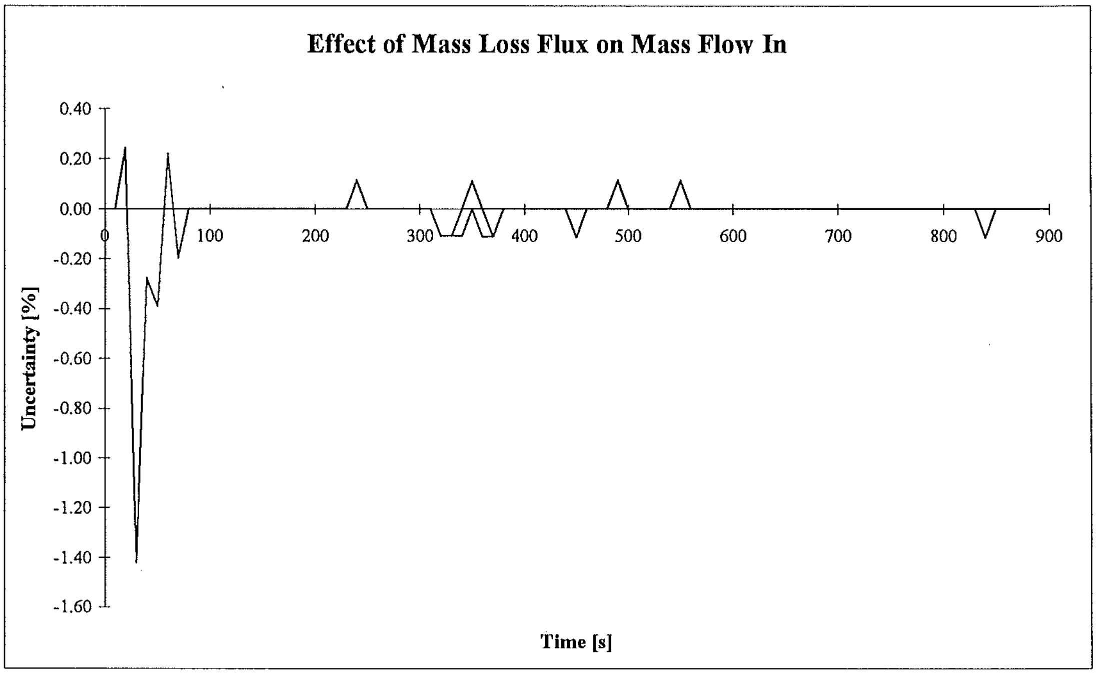

Effect of Mass Loss Flux on Upper Layer Temperature
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Mass Loss Flux on Lower Layer Temperature
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

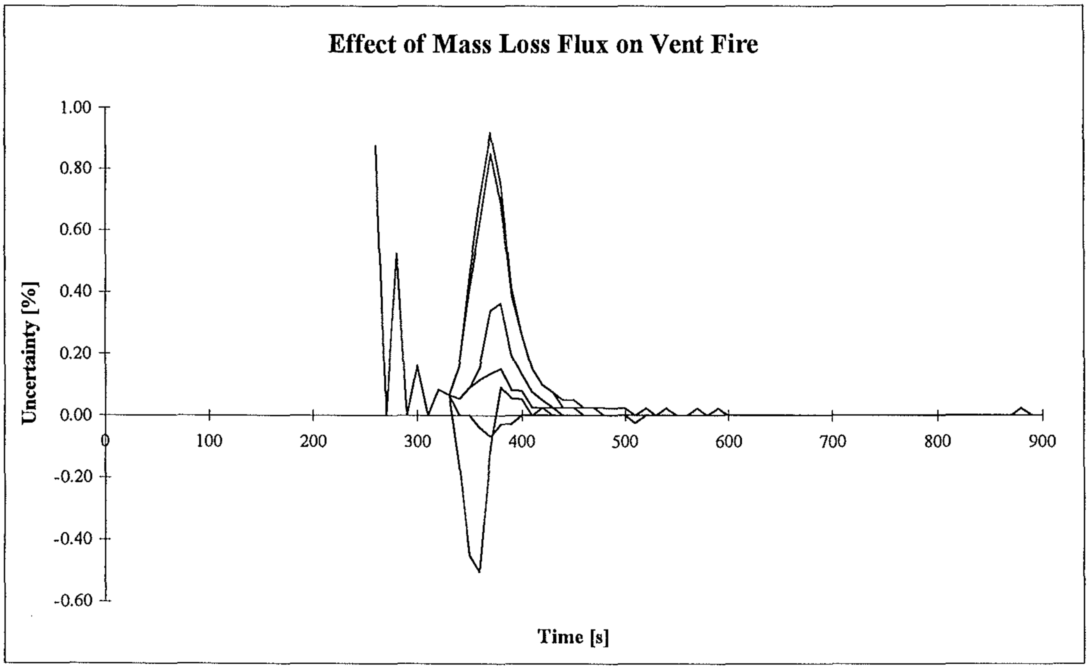

Effect of Mass Loss Flux on heat Release Rate
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



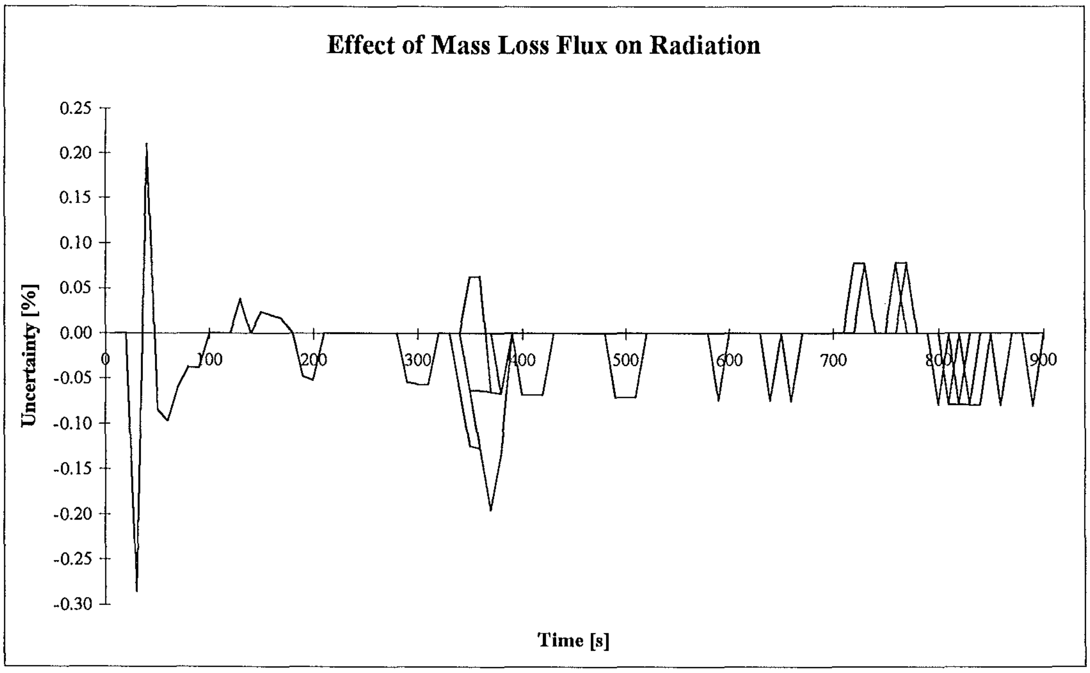
Effect of Mass Loss Flux on Mass Flow Out
Uncertainty [%]
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
100
200
300
400
500
600
700
800
900
Time [s]



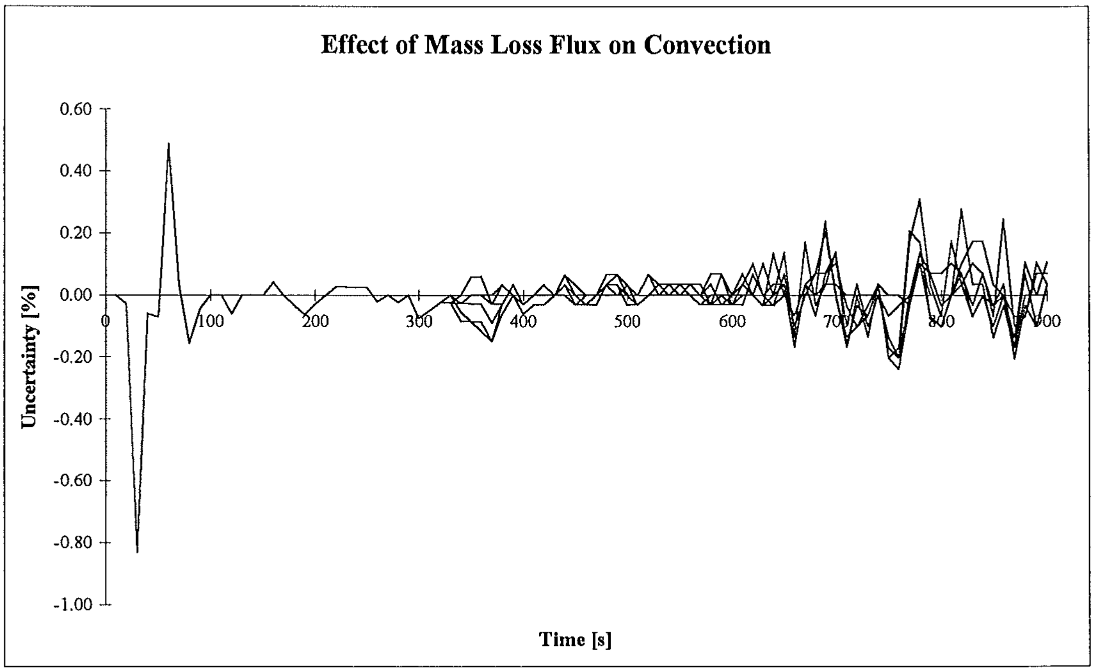
Effect of Mass Loss Flux on Mass Flow In
Uncertainty [%]
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
0
100
200
300
400
500
600
700
800
900
Time [s]



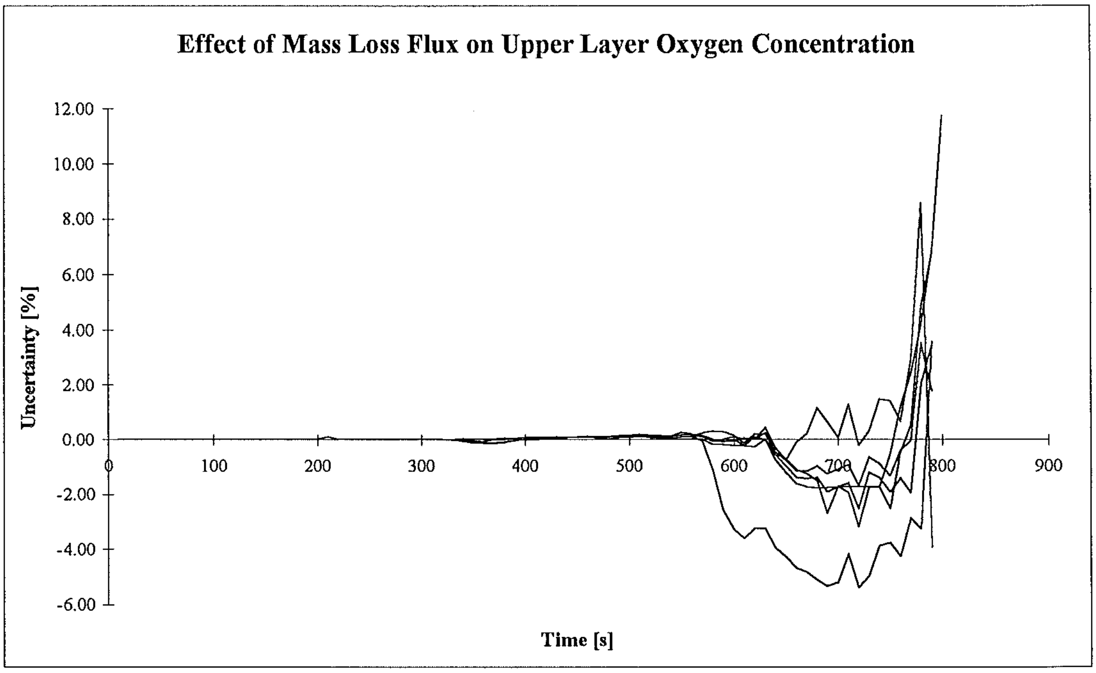
Effect of Mass Loss Flux on Vent Fire
Uncertainty [%]
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
0
100
200
300
400
500
600
700
800
900
Time [s]



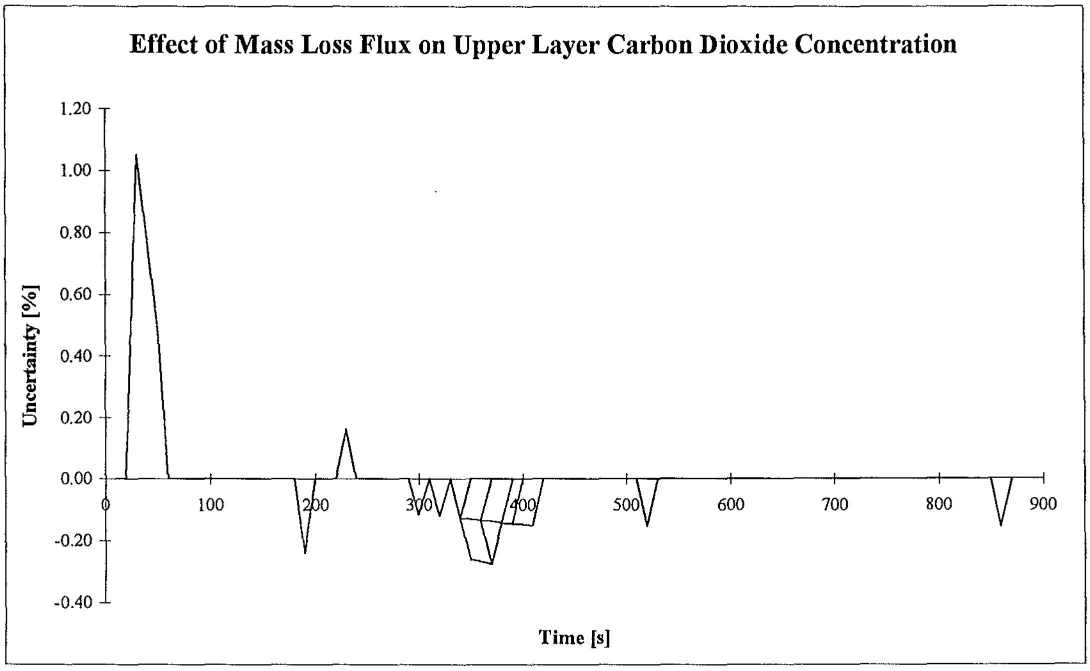
Effect of Mass Loss Flux on Radiation
Uncertainty [%]
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
0
100
200
300
400
500
600
700
800
900
Time [s]



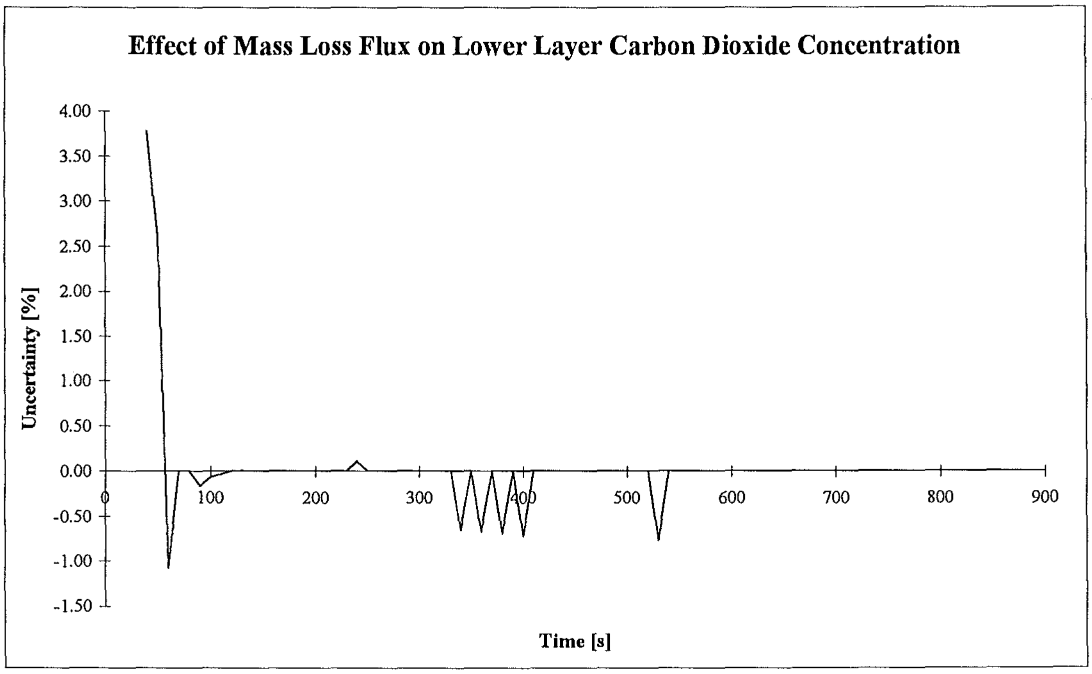
Effect of Mass Loss Flux on Convection
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



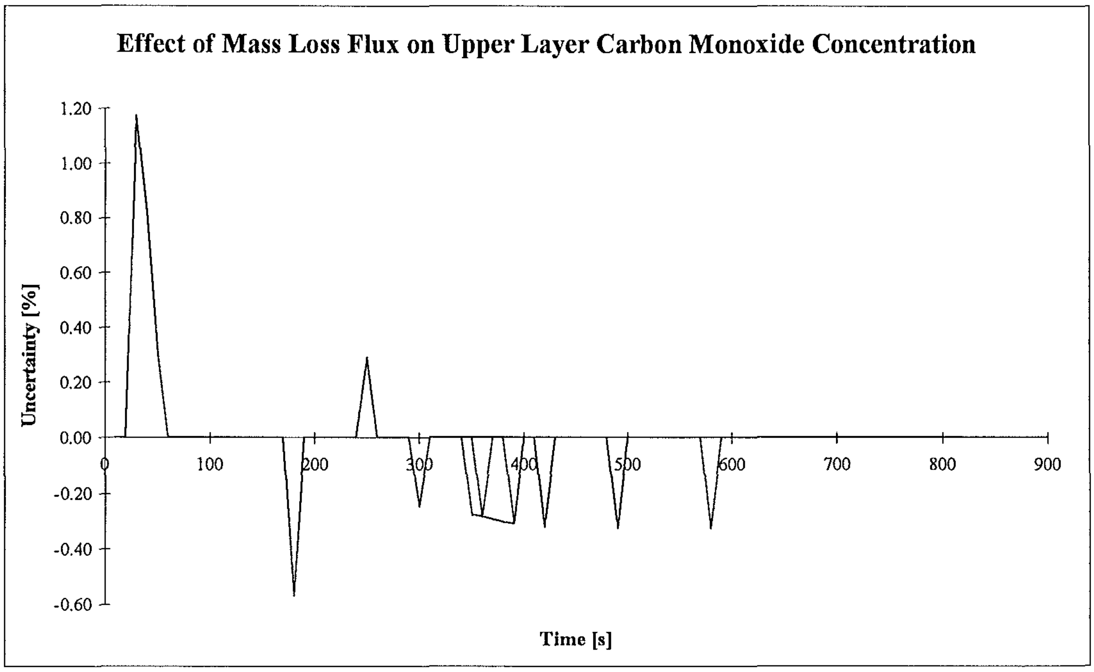
Effect of Mass Loss Flux on Upper Layer Oxygen Concentration
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

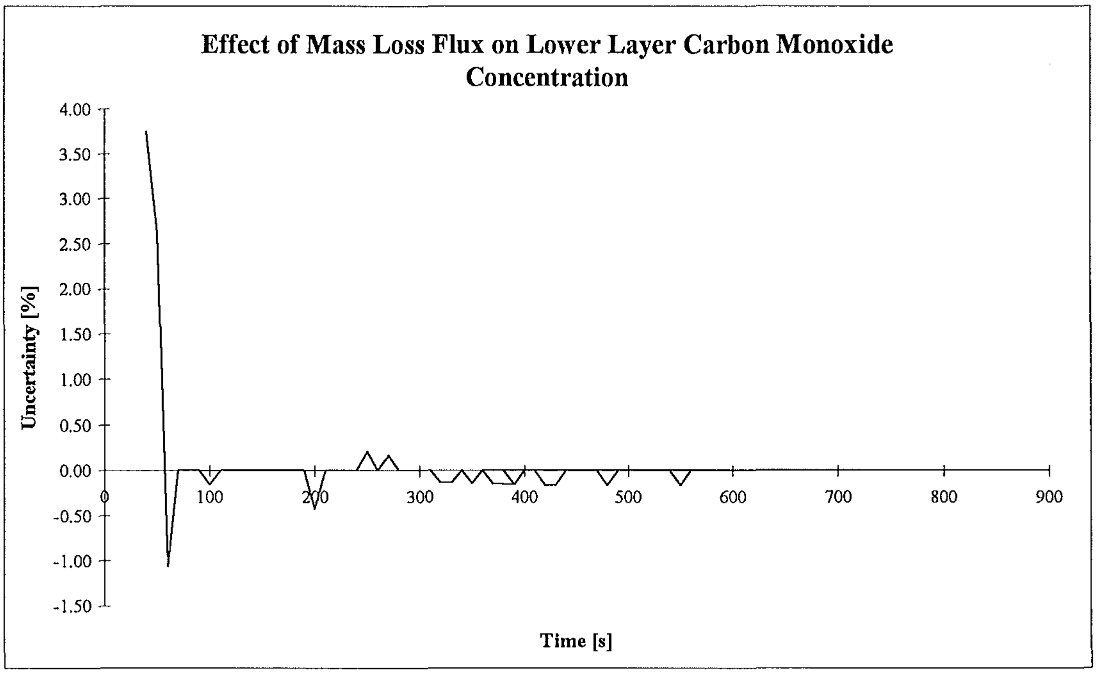


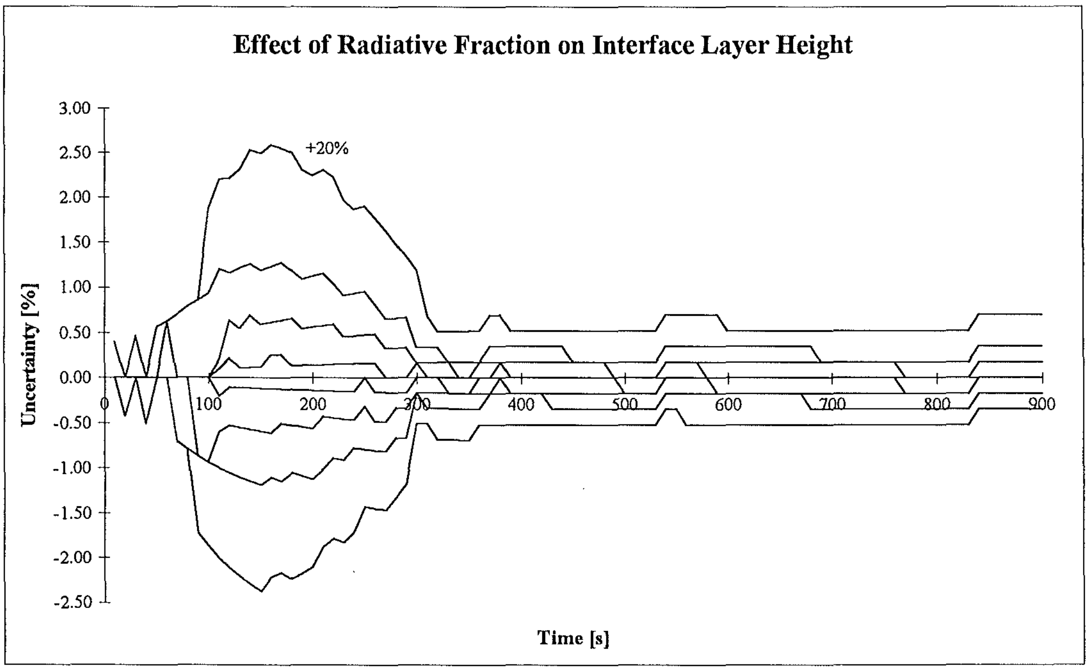
Effect of Mass Loss Flux on Upper Layer Carbon Dioxide Concentration
Uncertainty [%]
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
0
100
200
300
400
500
600
700
800
900
Time [s]

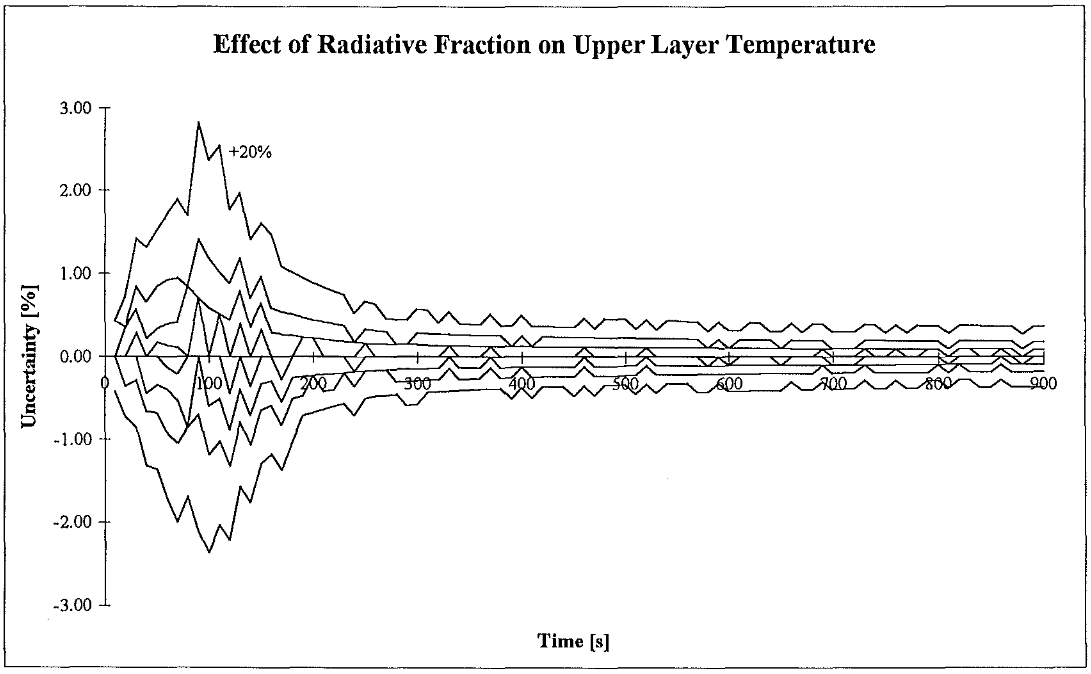


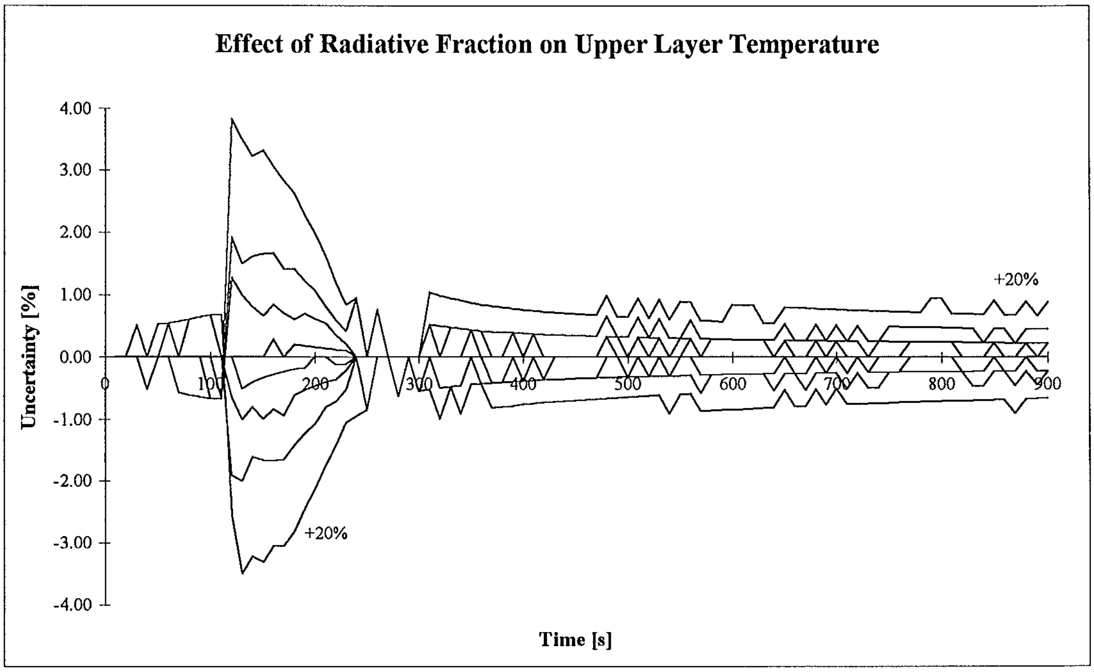
Effect of Mass Loss Flux on Lower Layer Carbon Dioxide Concentration
Uncertainty [%]
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0
100
200
300
400
500
600
700
800
900
Time [s]

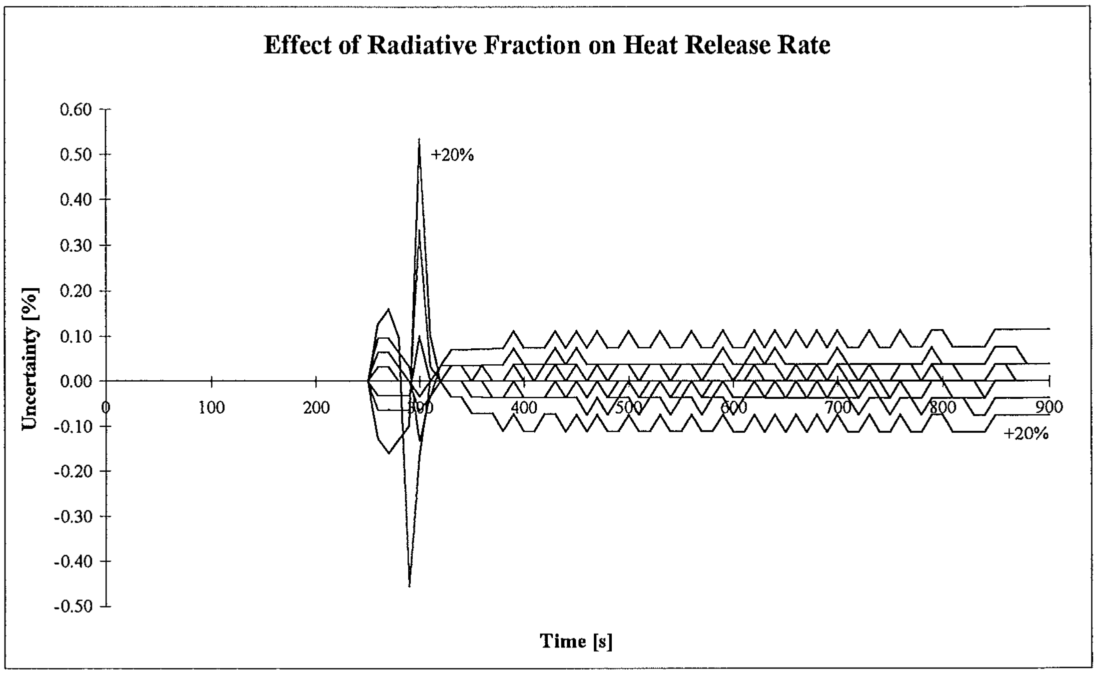

Effect of Mass Loss Flux on Upper Layer Carbon Monoxide Concentration
Uncertainty [%]
1.20
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
0
100
200
300
400
500
600
700
800
900
Time [s]

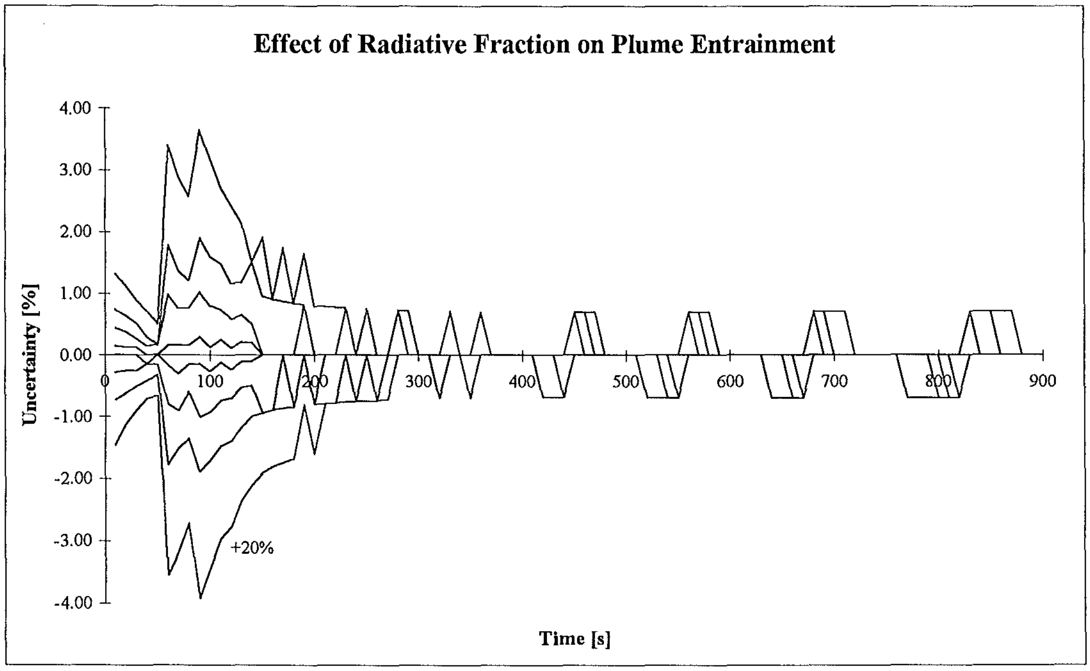

Effect of Mass Loss Flux on Lower Layer Carbon Monoxide Concentration
Uncertainty [%]
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Radiative Fraction on Interface Layer Height
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

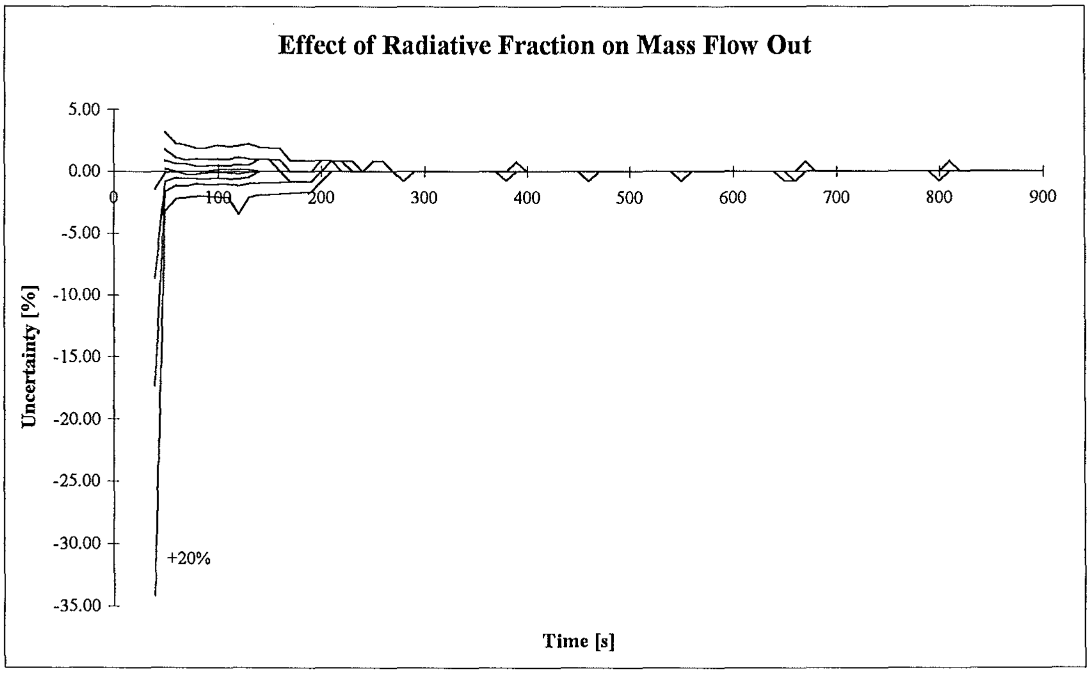

Effect of Radiative Fraction on Upper Layer Temperature
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Radiative Fraction on Upper Layer Temperature
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+20%
Time [s]

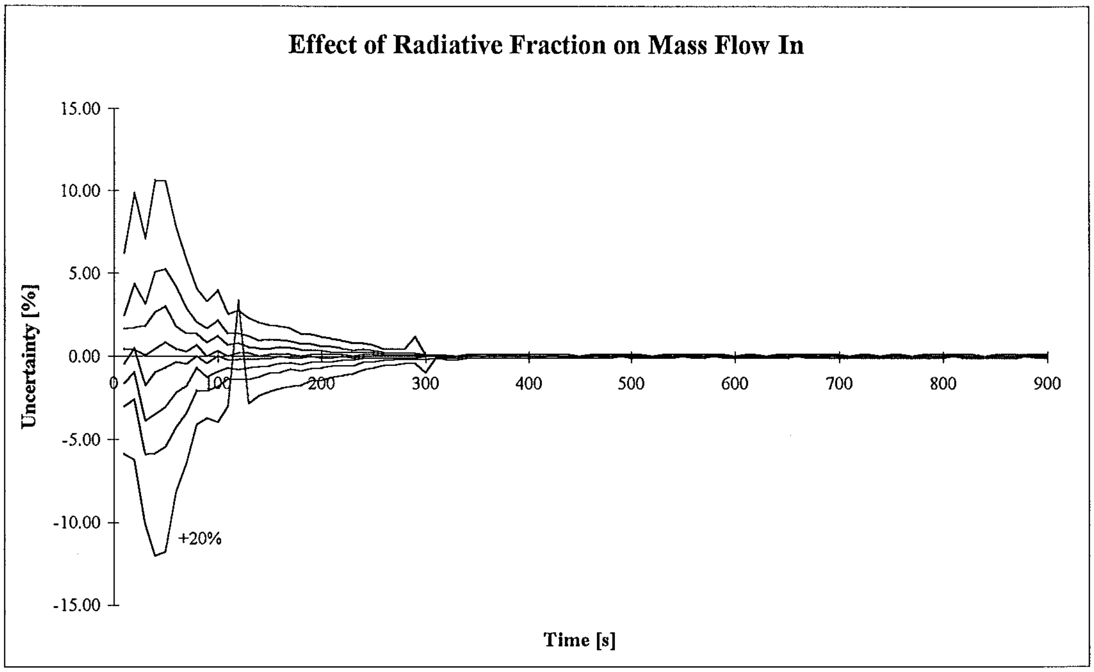

Effect of Radiative Fraction on Heat Release Rate
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+20%
Time [s]

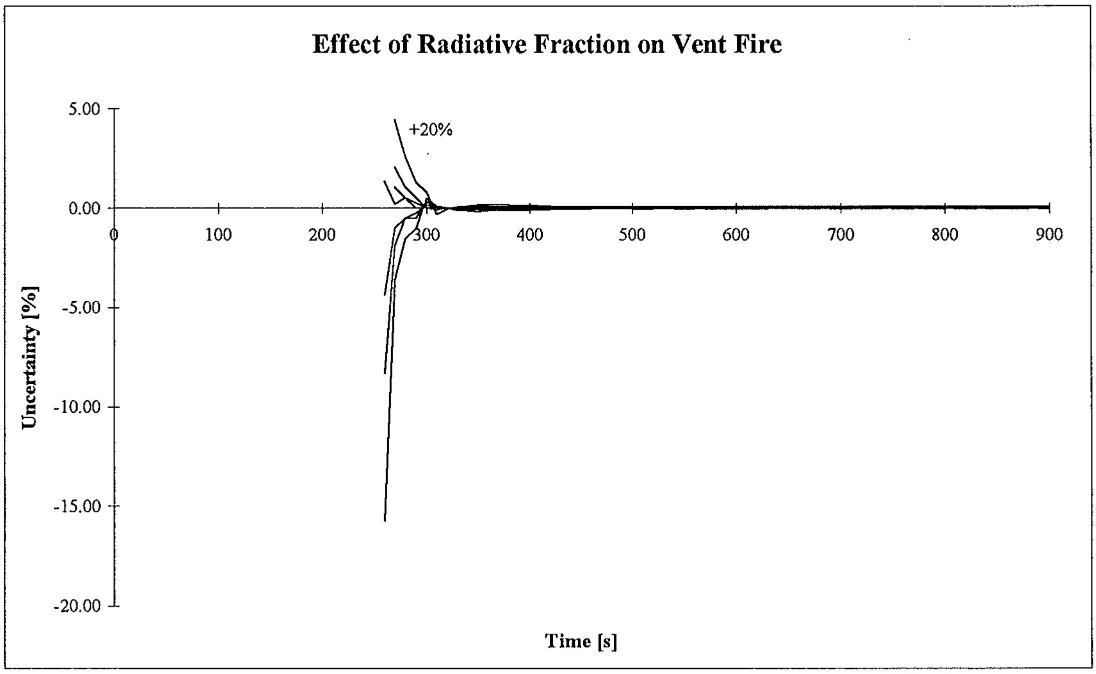


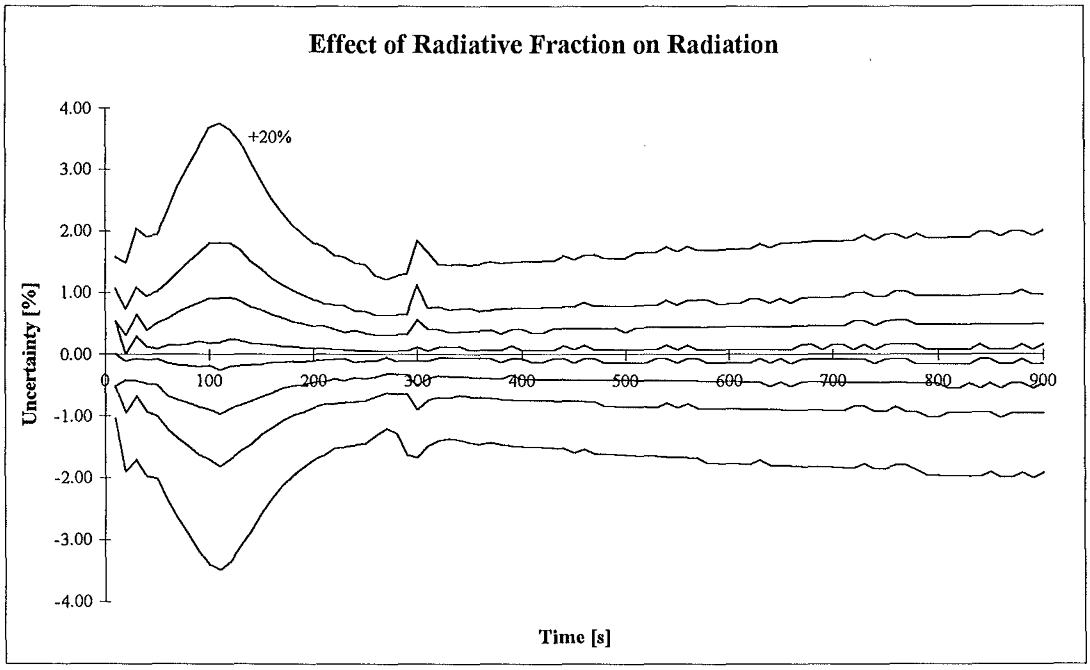
Effect of Radiative Fraction on Plume Entrainment
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

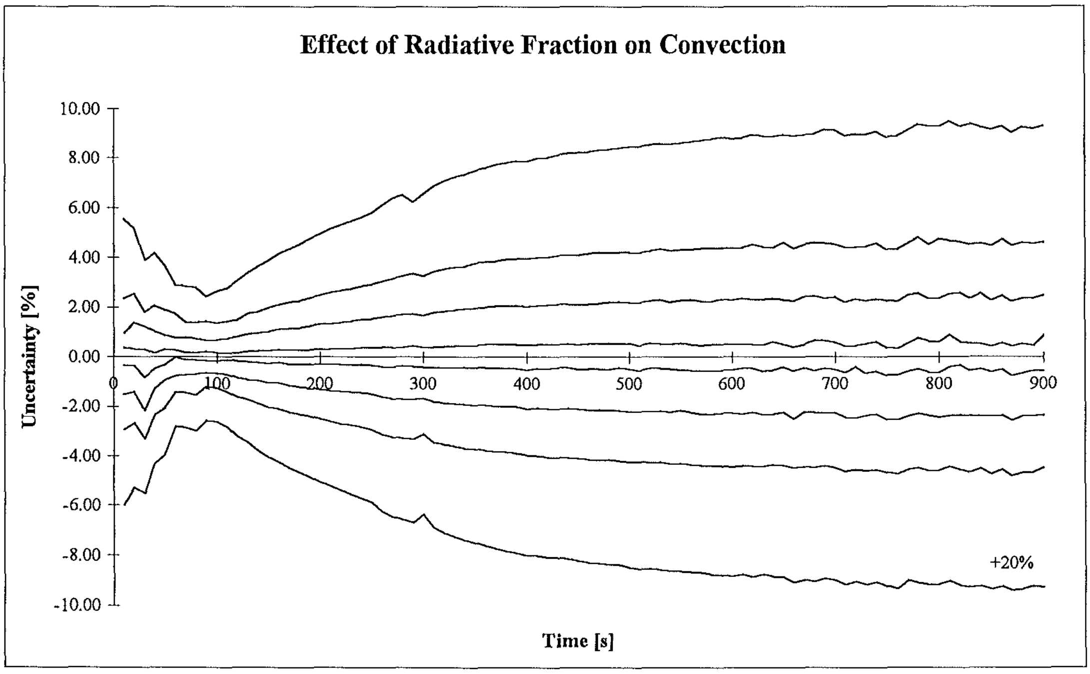


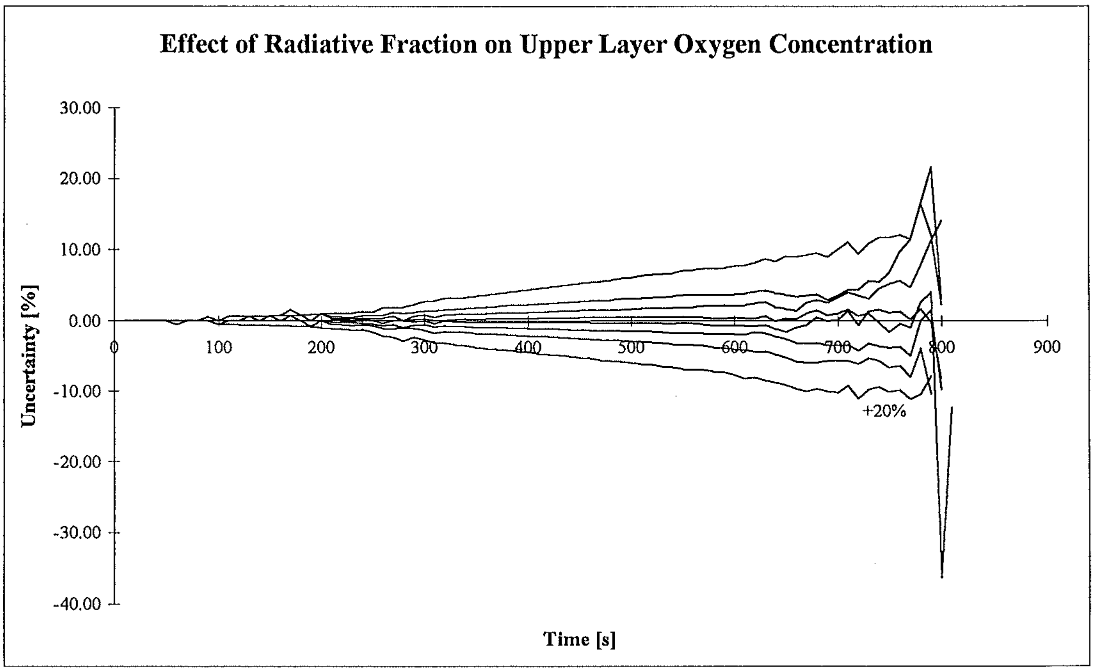
Effect of Radiative Fraction on Mass Flow Out
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Radiative Fraction on Mass Flow In
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

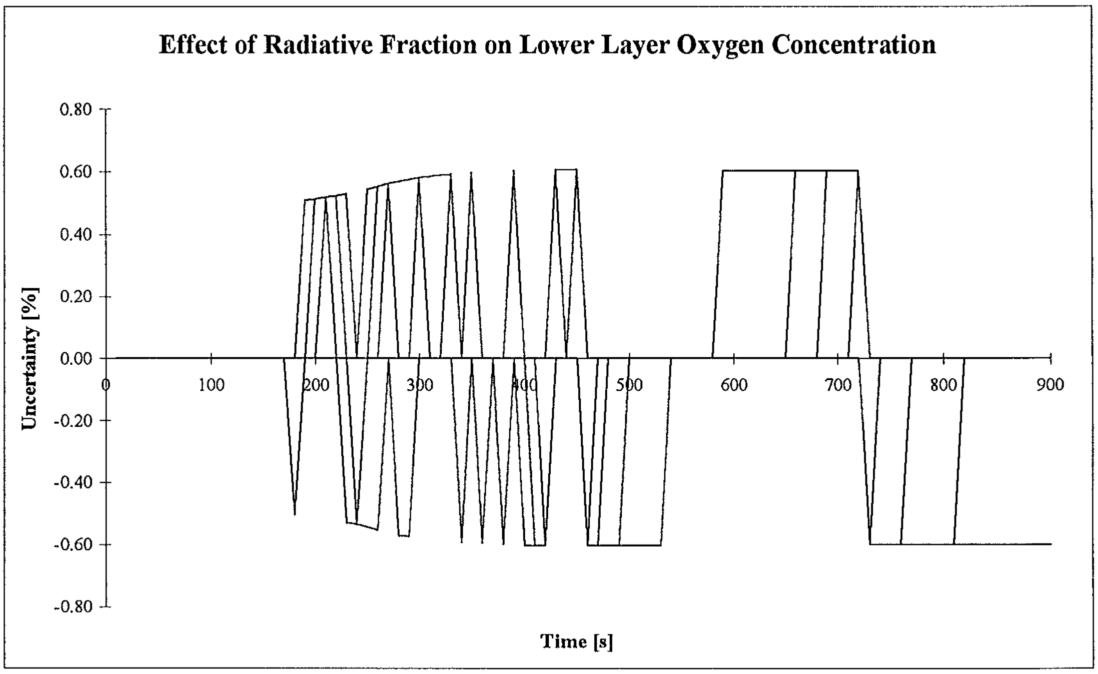

Effect of Radiative Fraction on Vent Fire
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Radiative Fraction on Radiation
+20%
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

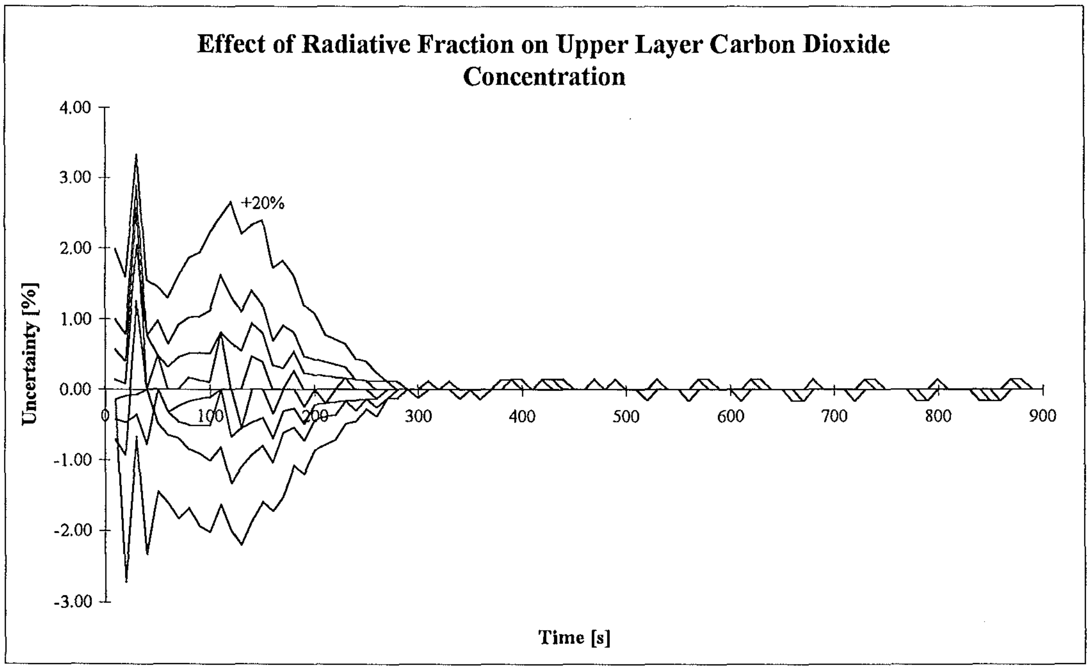

Effect of Radiative Fraction on Convection
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

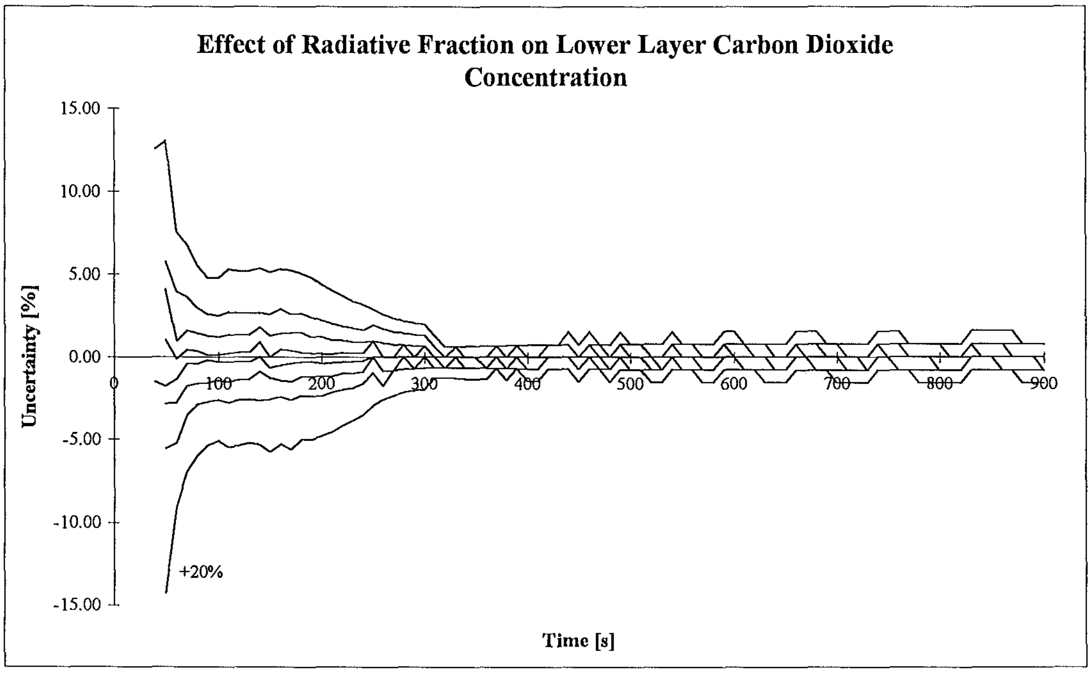


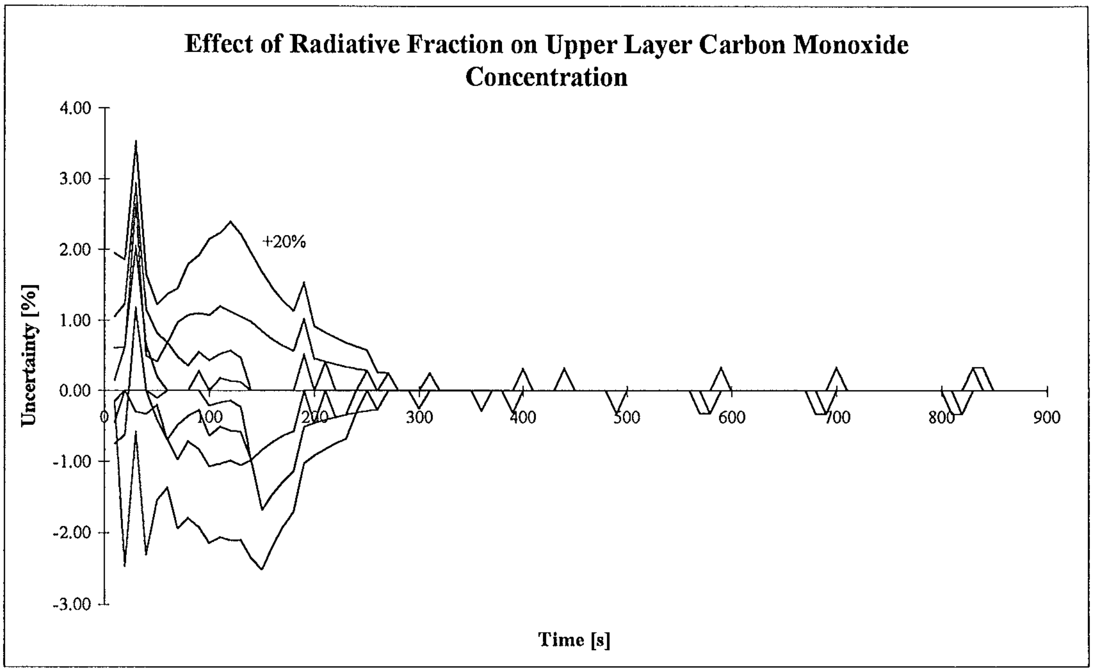
Effect of Radiative Fraction on Upper Layer Oxygen Concentration
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



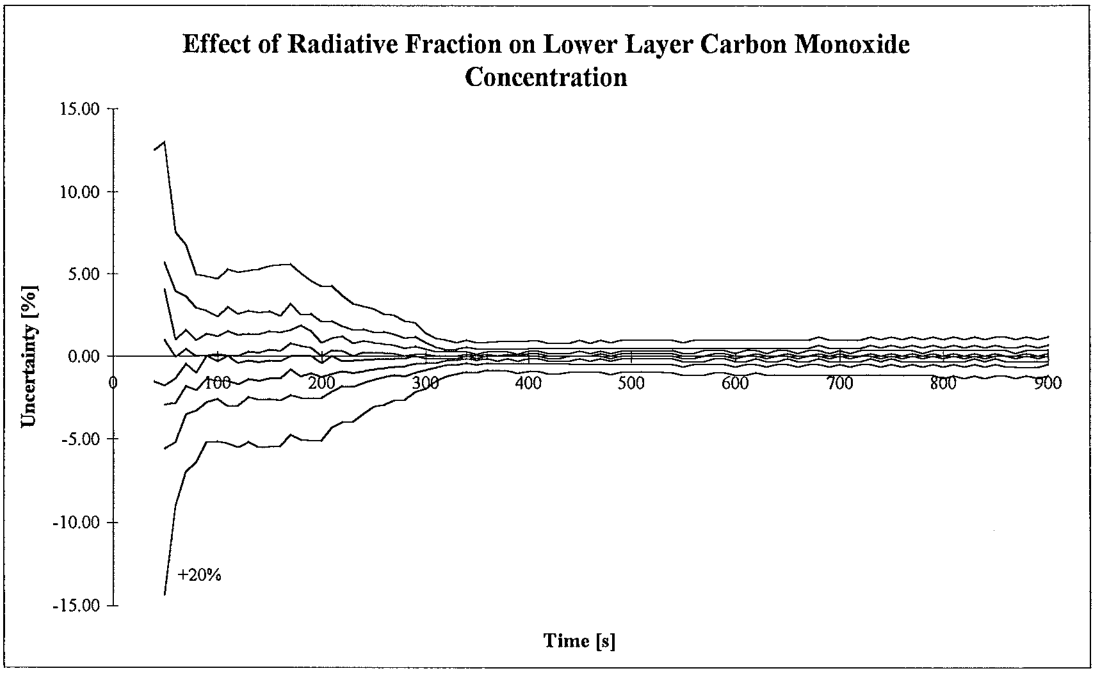
Effect of Radiative Fraction on Lower Layer Oxygen Concentration
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Radiative Fraction on Upper Layer Carbon Dioxide Concentration
Uncertainty [%]
Time [s]
+20%
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
0
100
200
300
400
500
600
700
800
900

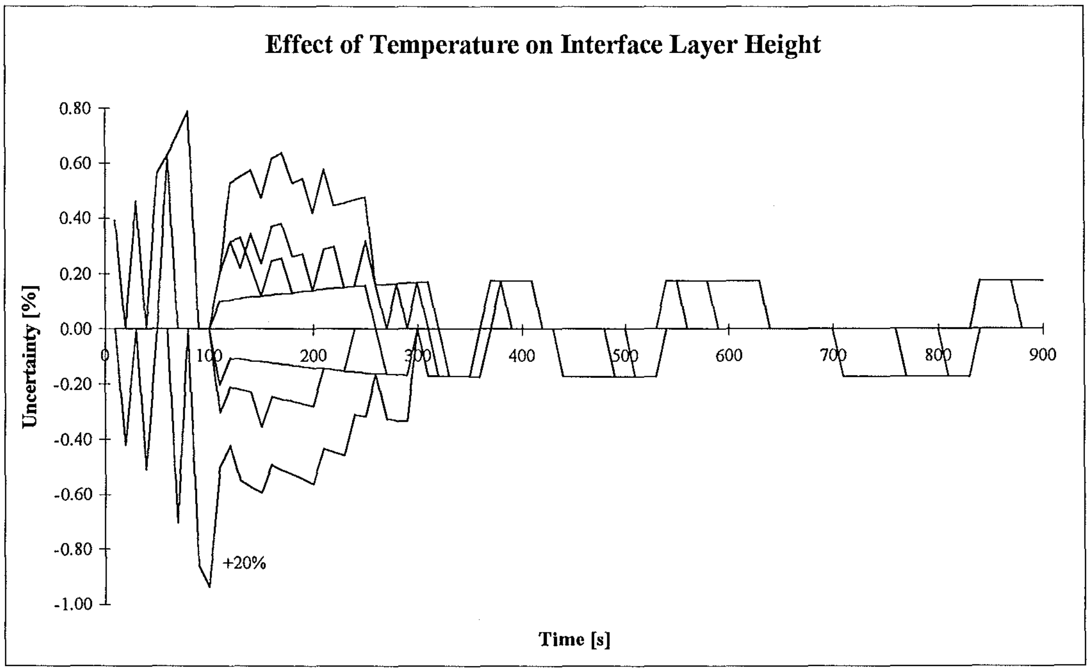

Effect of Radiative Fraction on Lower Layer Carbon Dioxide Concentration
Uncertainty [%]
Time [s]
+20%
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
0
100
200
300
400
500
600
700
800
900

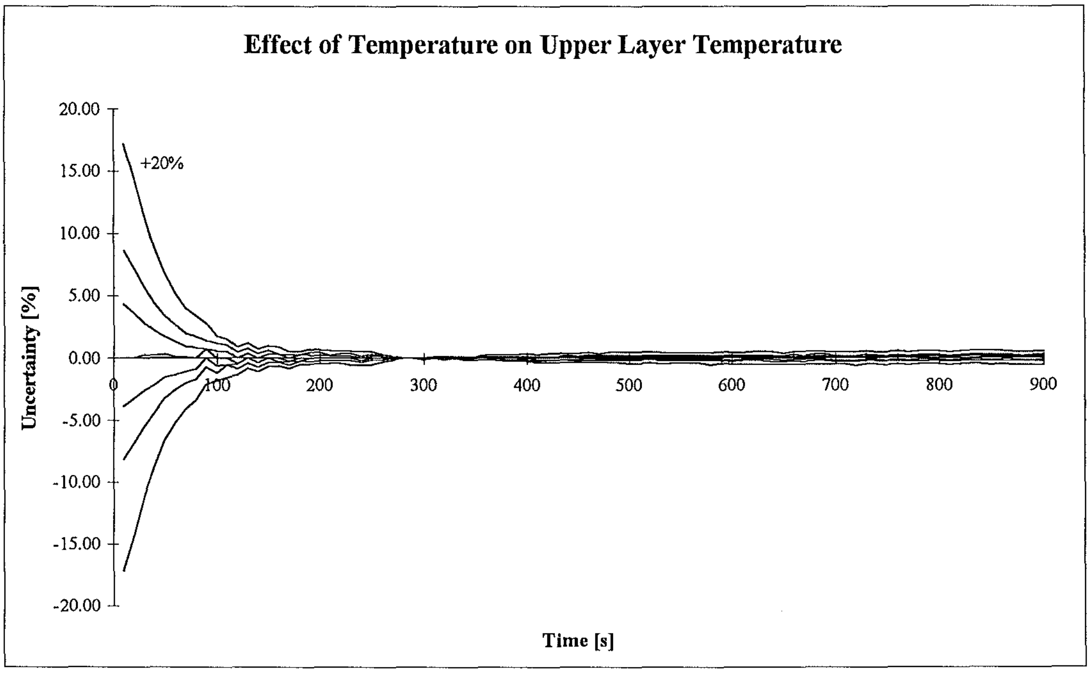


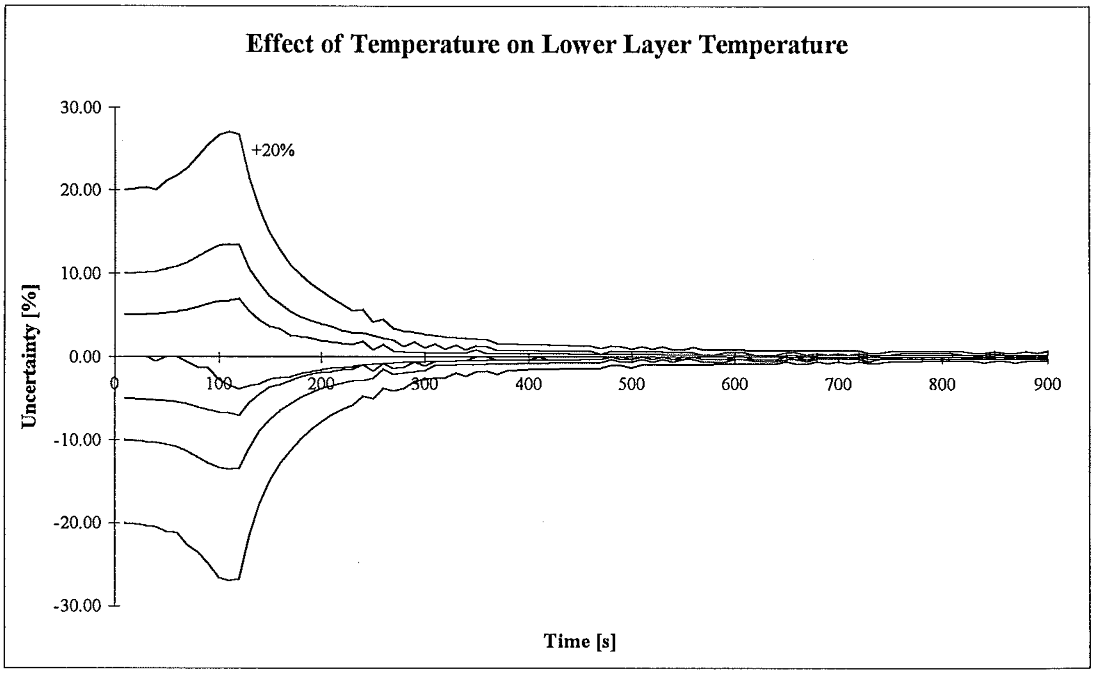
Effect of Radiative Fraction on Upper Layer Carbon Monoxide Concentration
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]



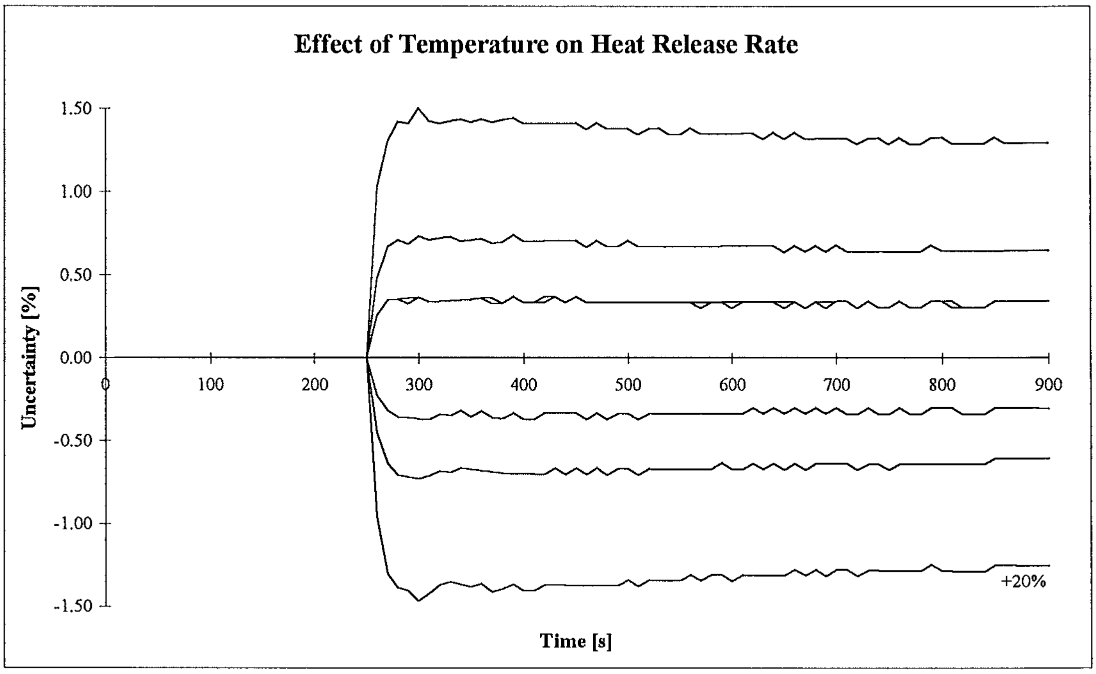
Effect of Radiative Fraction on Lower Layer Carbon Monoxide Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Temperature on Interface Layer Height
Uncertainty [%]
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

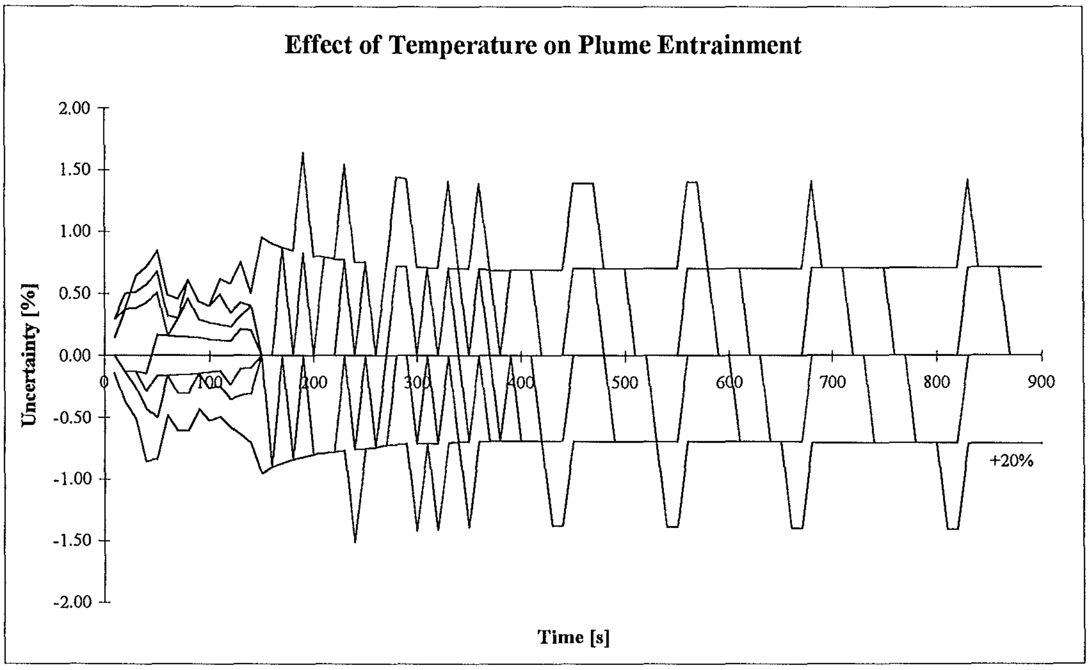

Effect of Temperature on Upper Layer Temperature
Uncertainty [%]
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

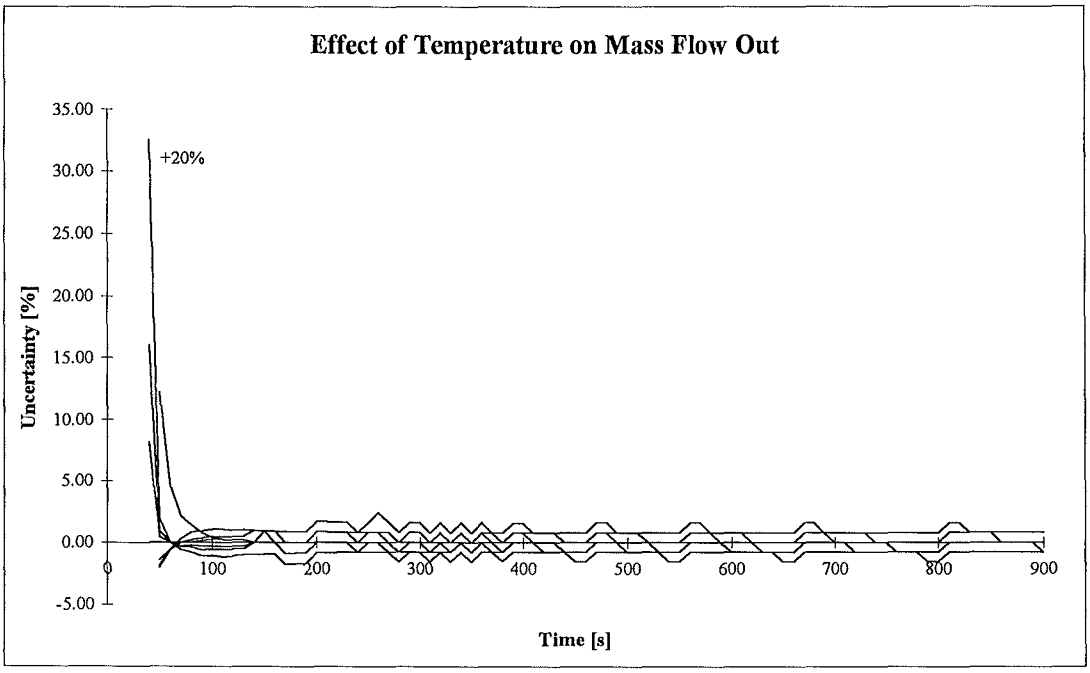


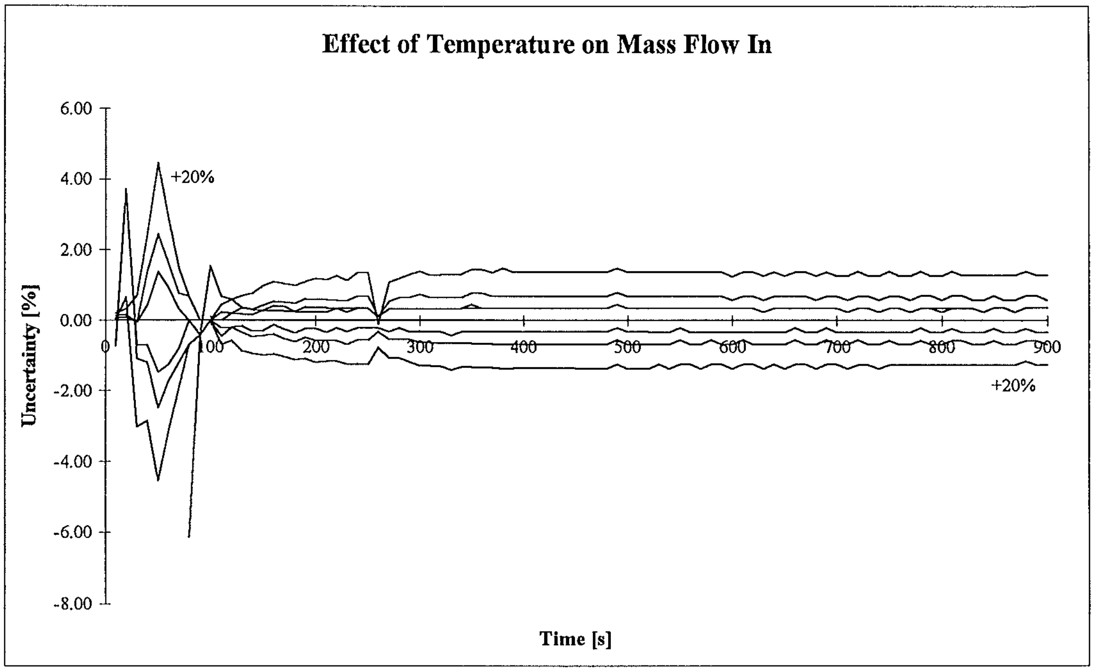
Effect of Temperature on Lower Layer Temperature
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

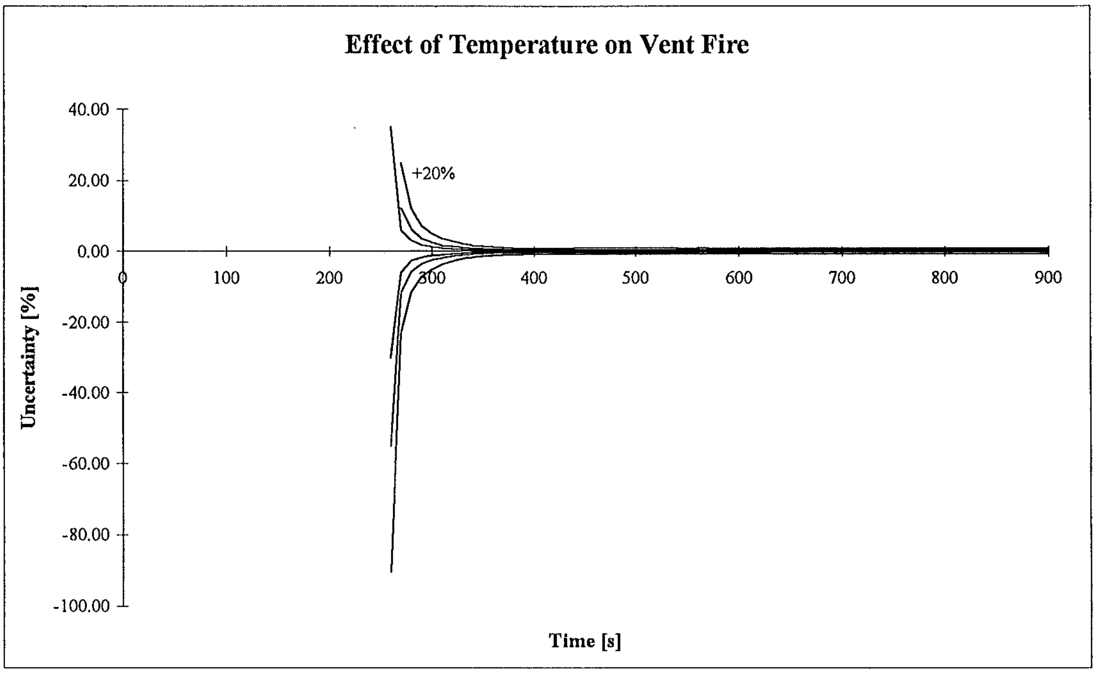


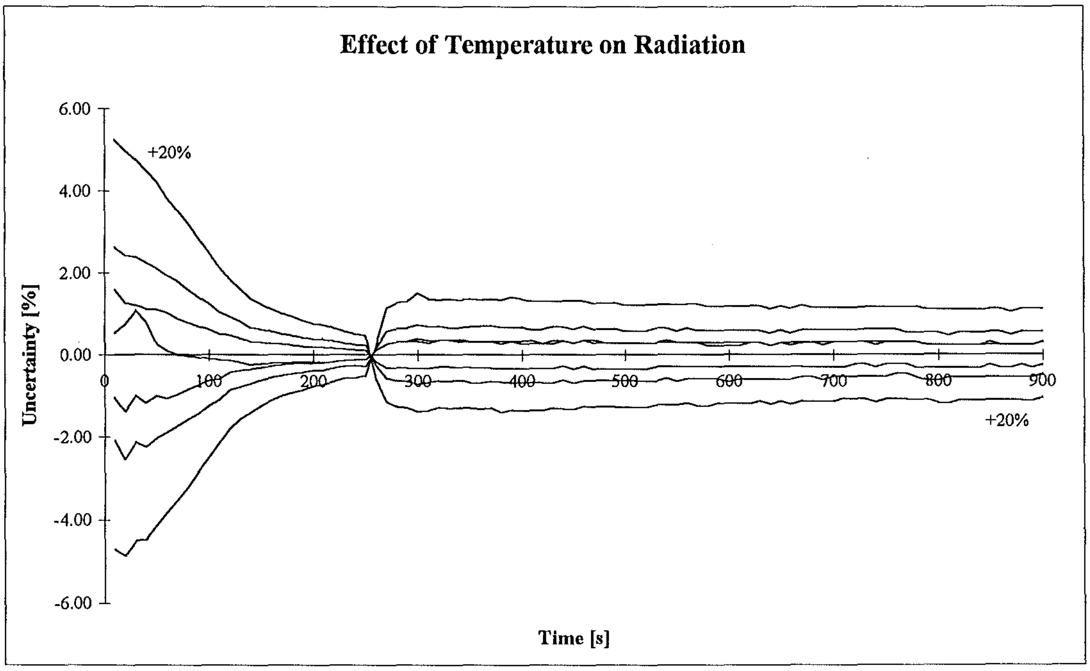
Effect of Temperature on Heat Release Rate
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

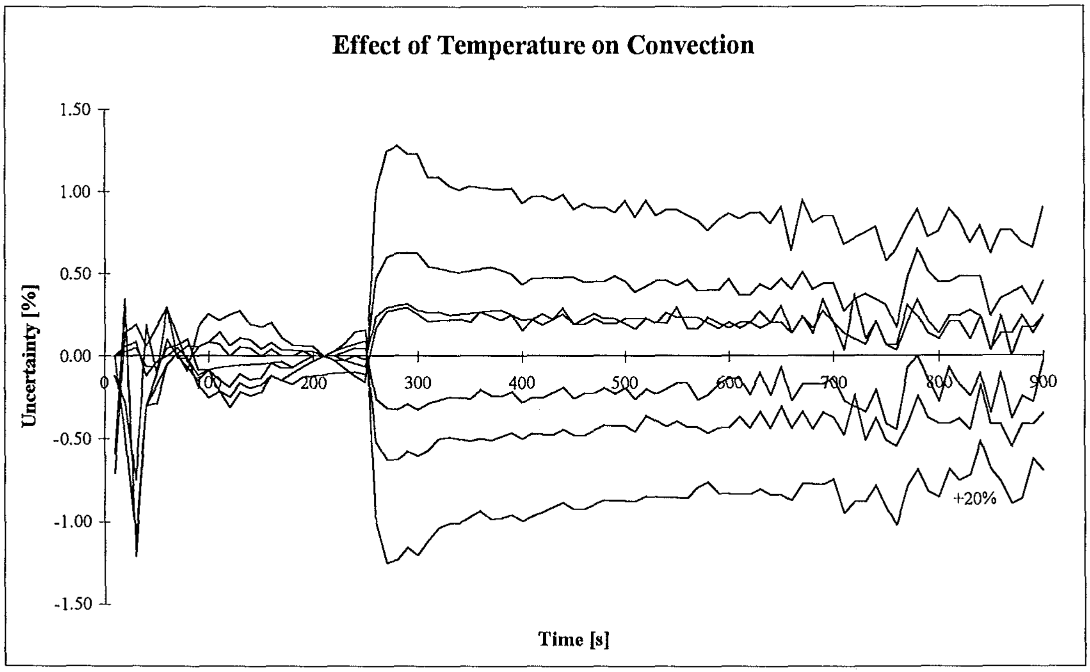

Effect of Temperature on Plume Entrainment
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

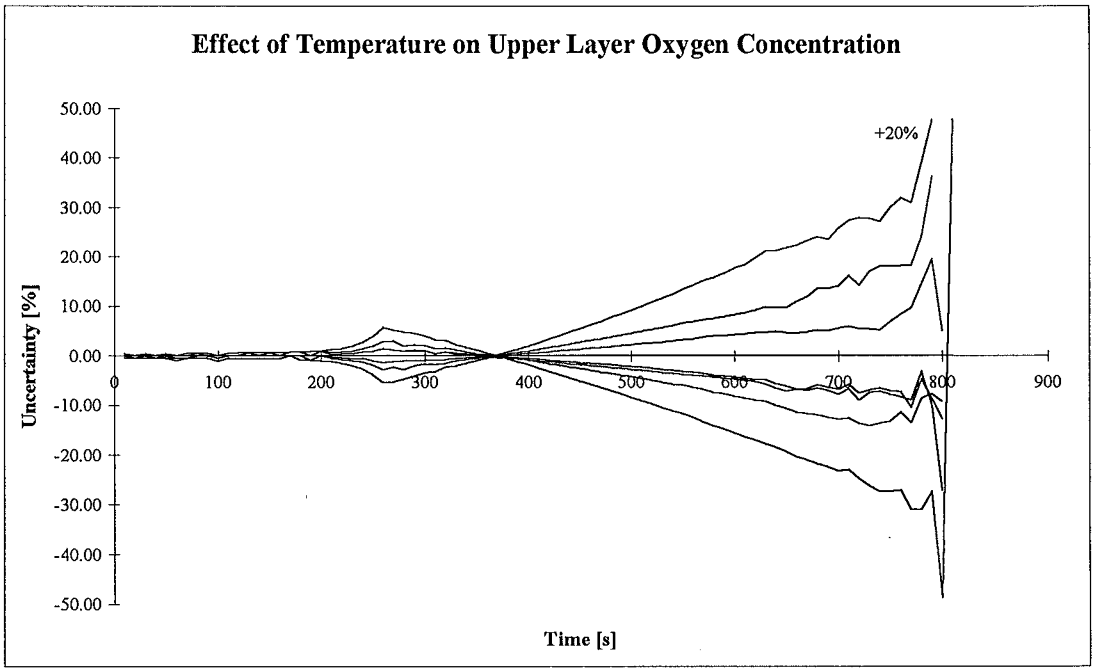

Effect of Temperature on Mass Flow Out
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]

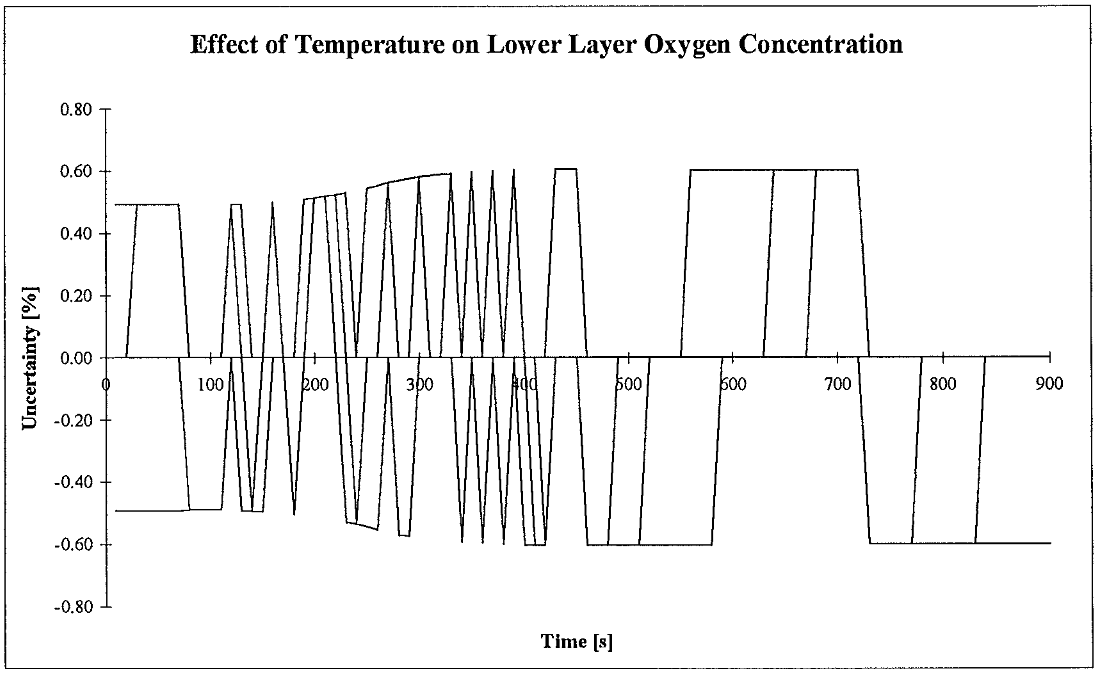

Effect of Temperature on Mass Flow In
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+20%
Time [s]

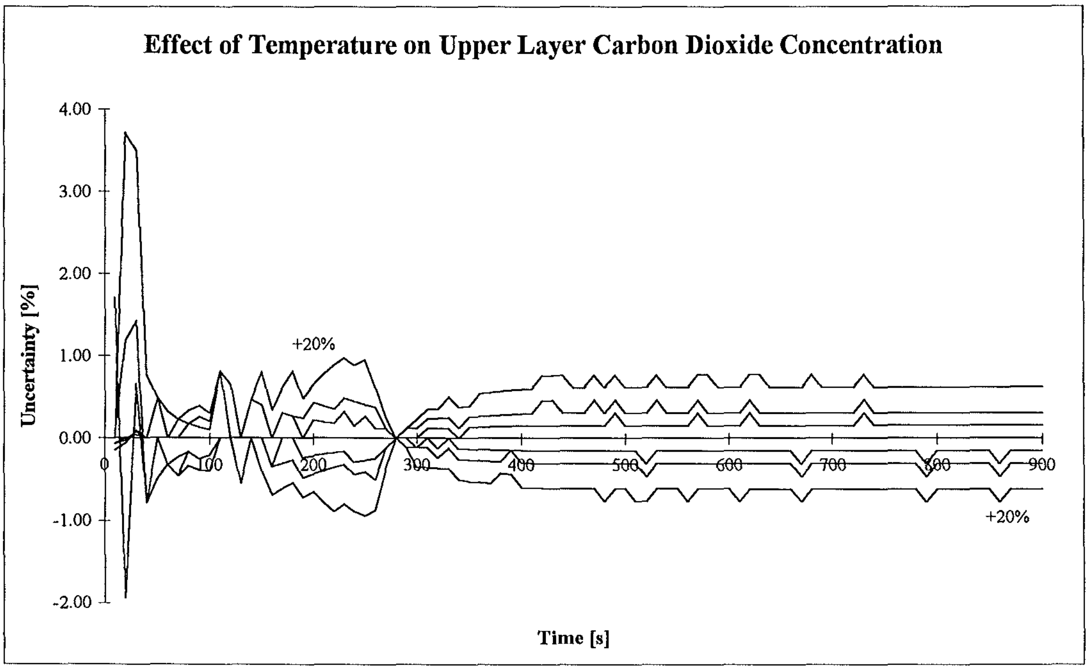

Effect of Temperature on Vent Fire
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Temperature on Radiation
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

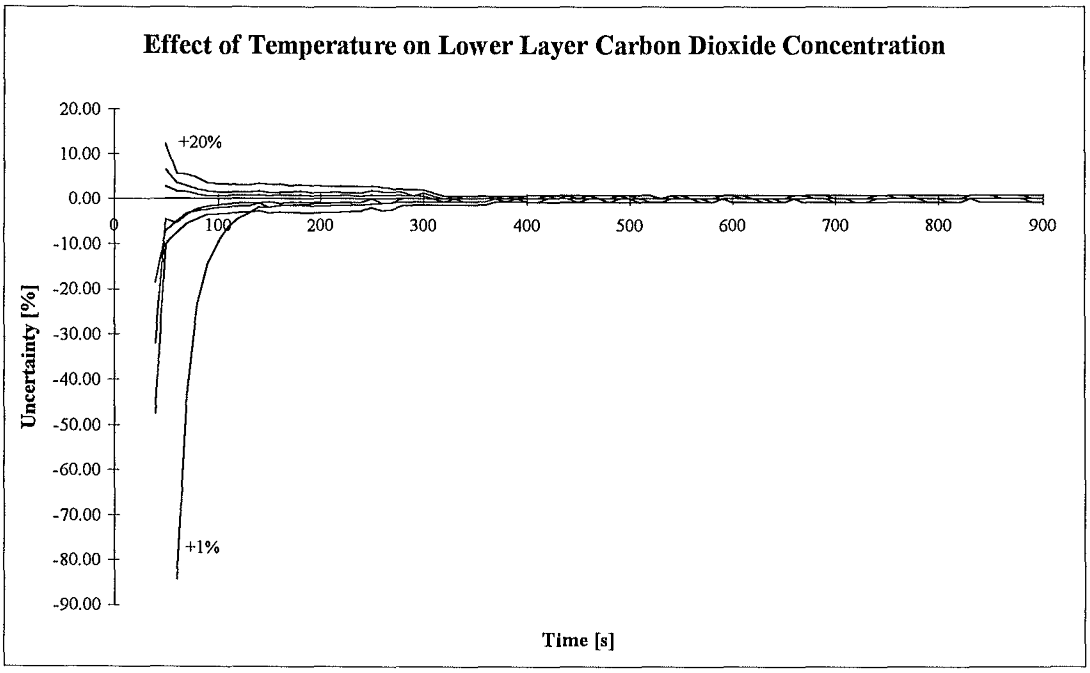

Effect of Temperature on Convection
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Temperature on Upper Layer Oxygen Concentration
+20%
Uncertainty [%]
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
0
100
200
300
400
500
600
700
800
900
Time [s]

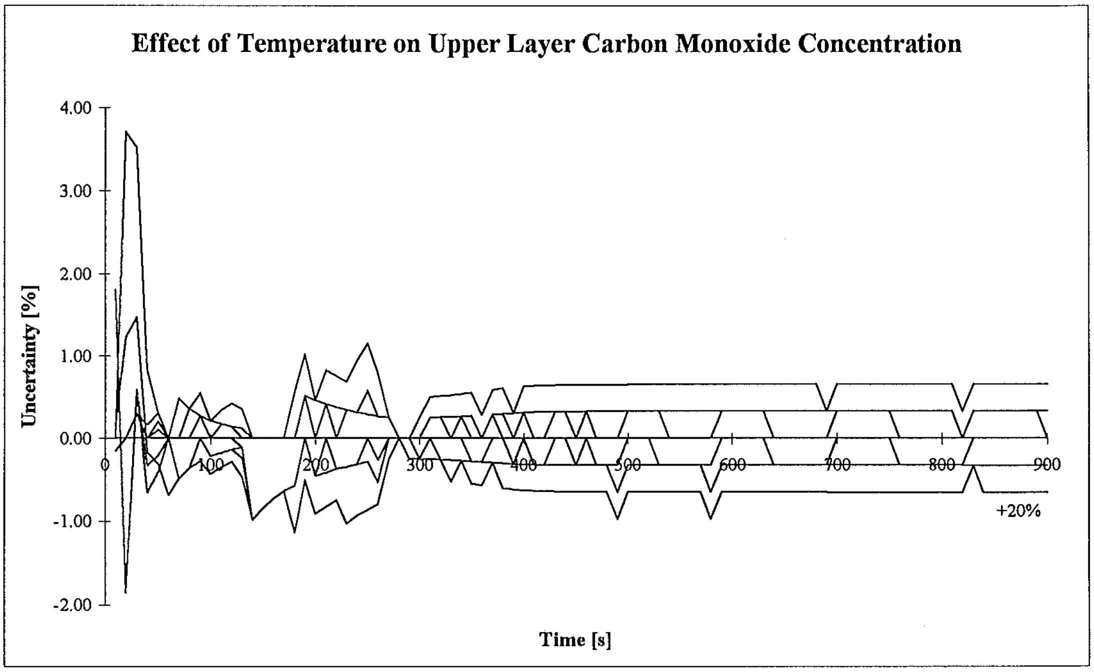

Effect of Temperature on Lower Layer Oxygen Concentration
Uncertainty [%]
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
0
100
200
300
400
500
600
700
800
900
Time [s]



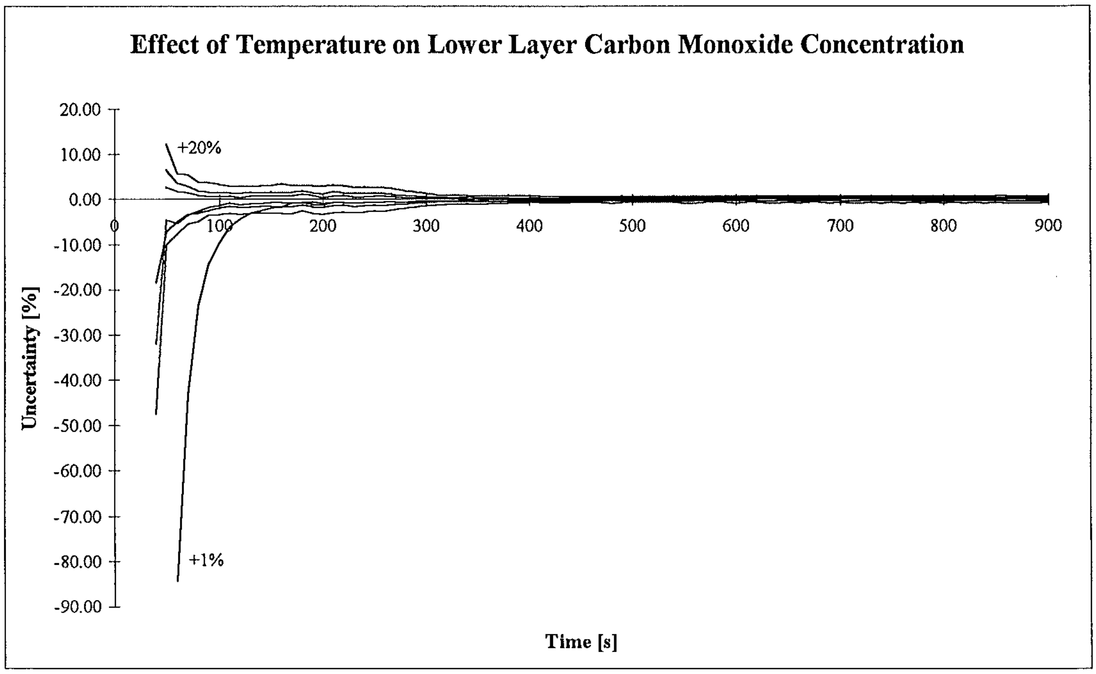
Effect of Temperature on Upper Layer Carbon Dioxide Concentration
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



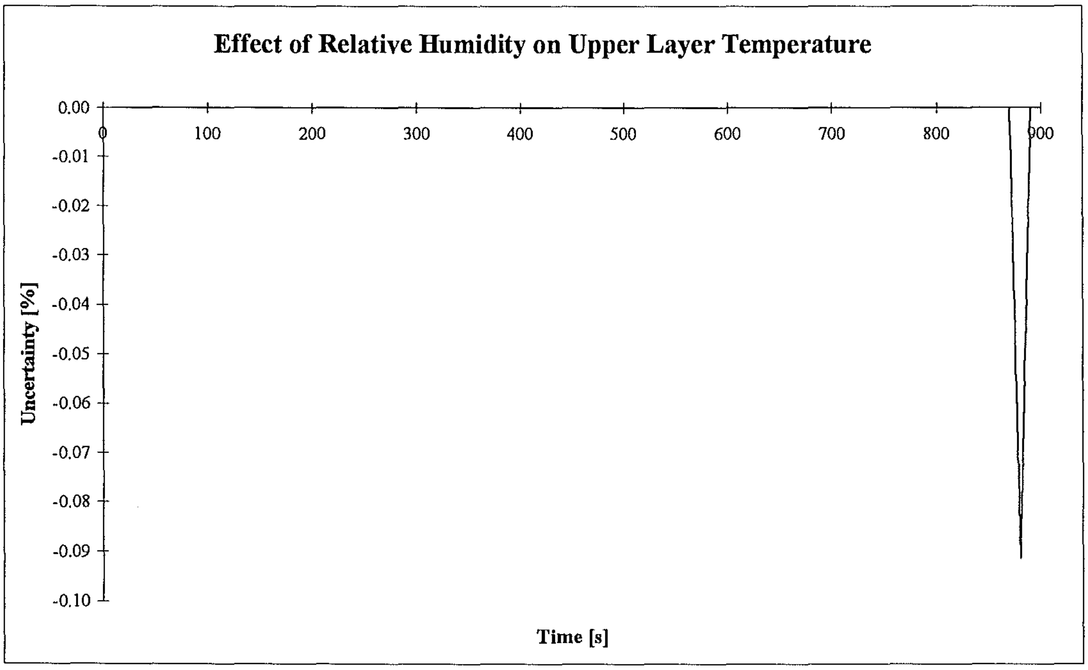
Effect of Temperature on Lower Layer Carbon Dioxide Concentration
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
+1%
Time [s]

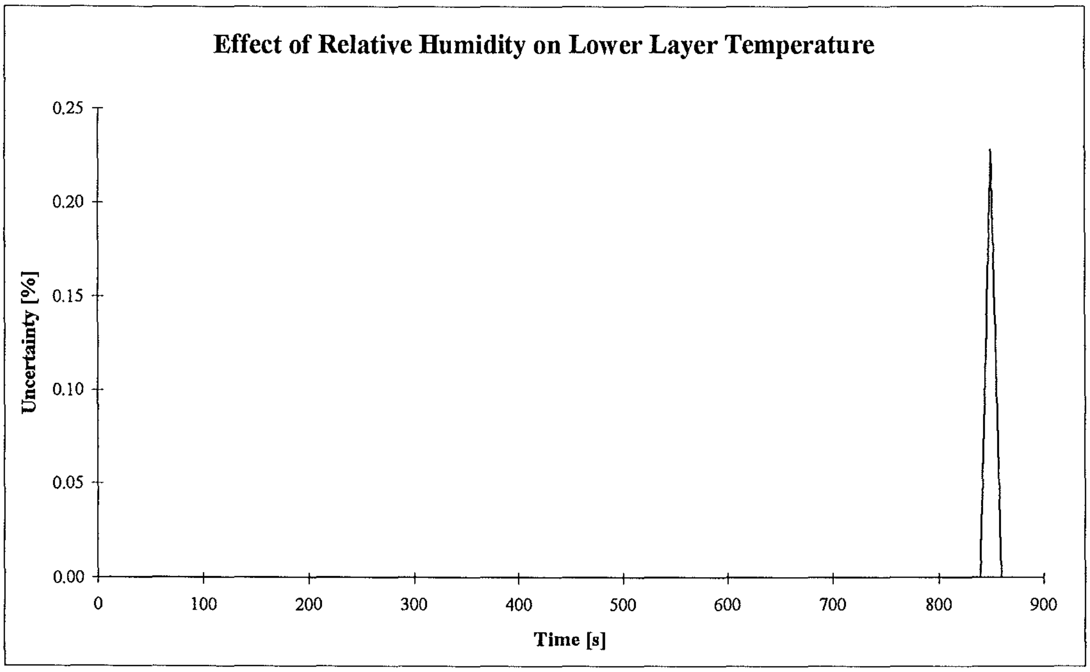


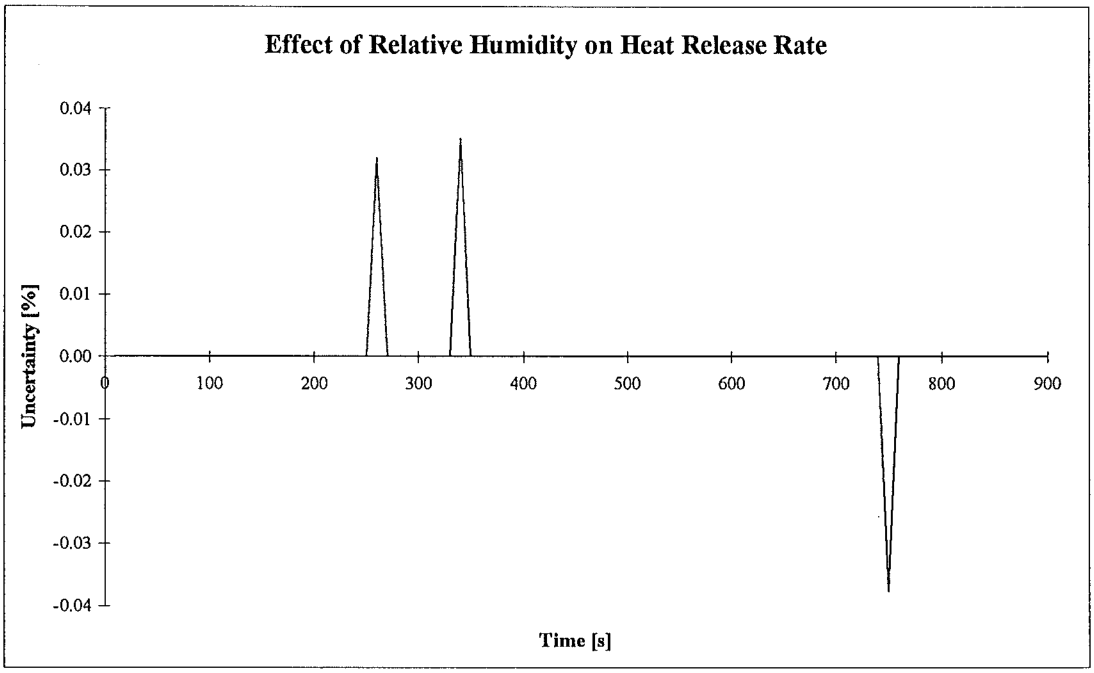
Effect of Temperature on Upper Layer Carbon Monoxide Concentration
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



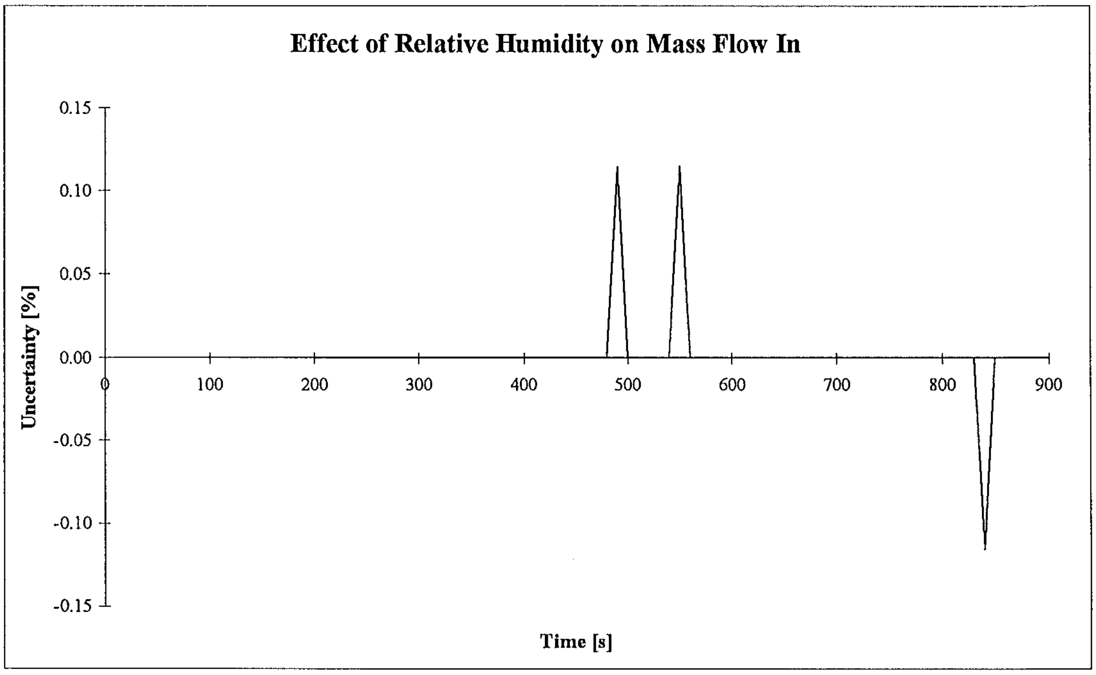
Effect of Temperature on Lower Layer Carbon Monoxide Concentration
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+1%
Time [s]


Effect of Relative Humidity on Upper Layer Temperature
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

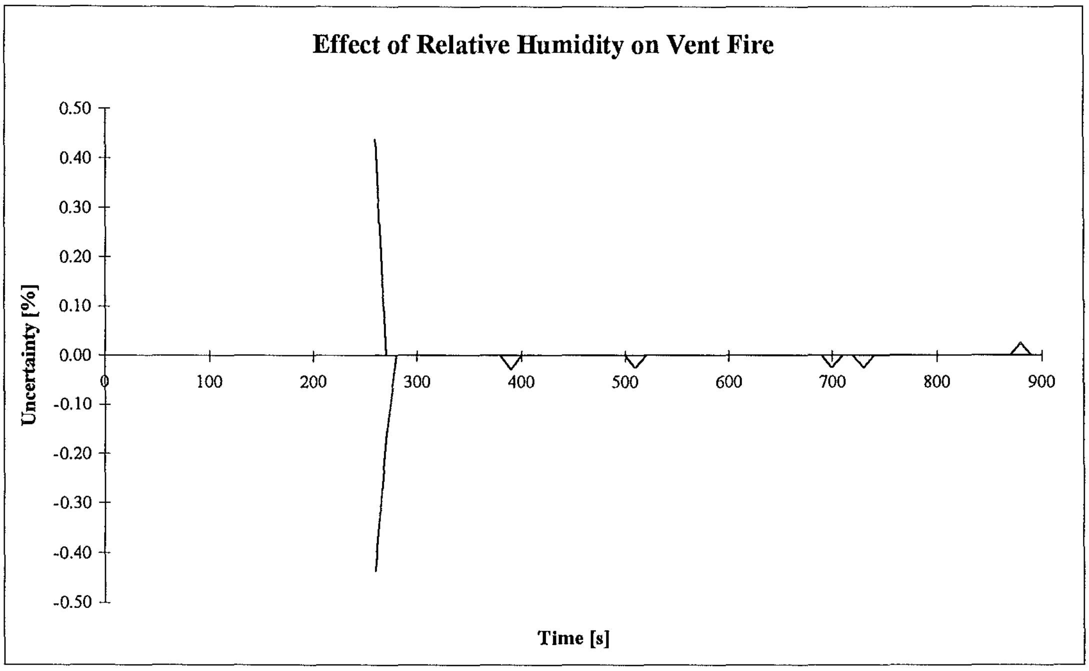

Effect of Relative Humidity on Lower Layer Temperature
0.25
0.20
0.15
0.10
0.05
0.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



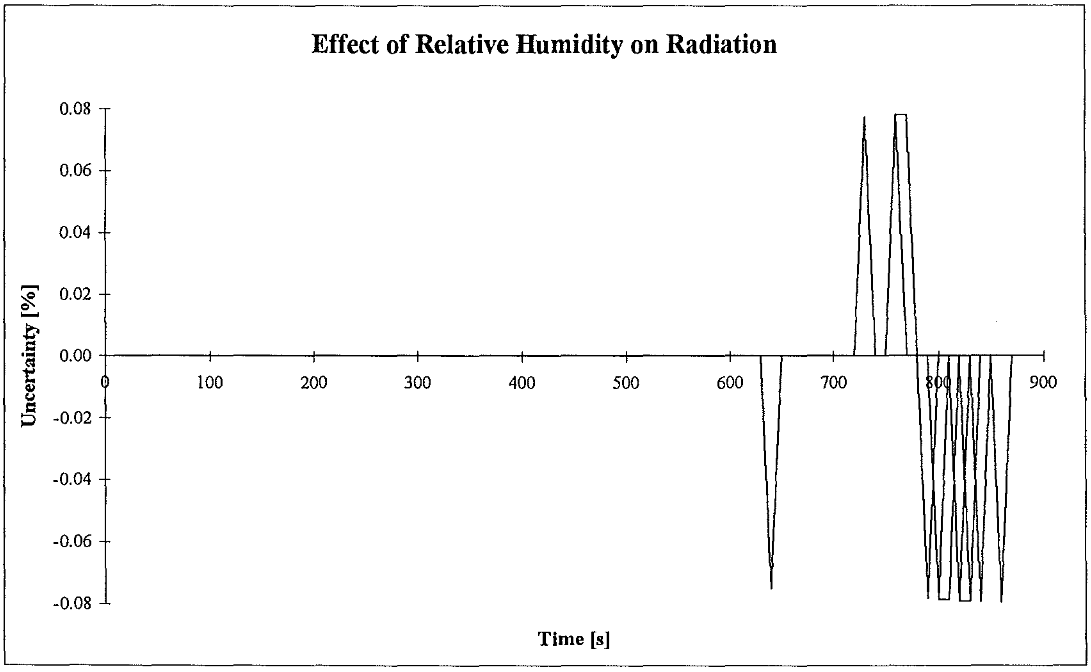
Effect of Relative Humidity on Heat Release Rate
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



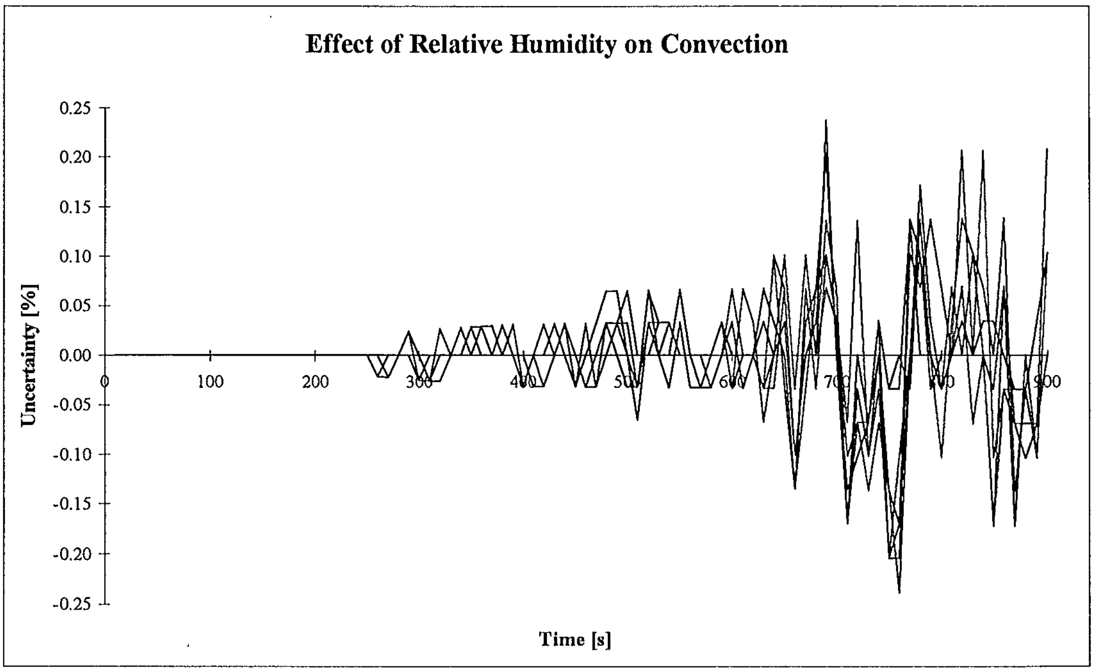
Effect of Relative Humidity on Mass Flow In
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

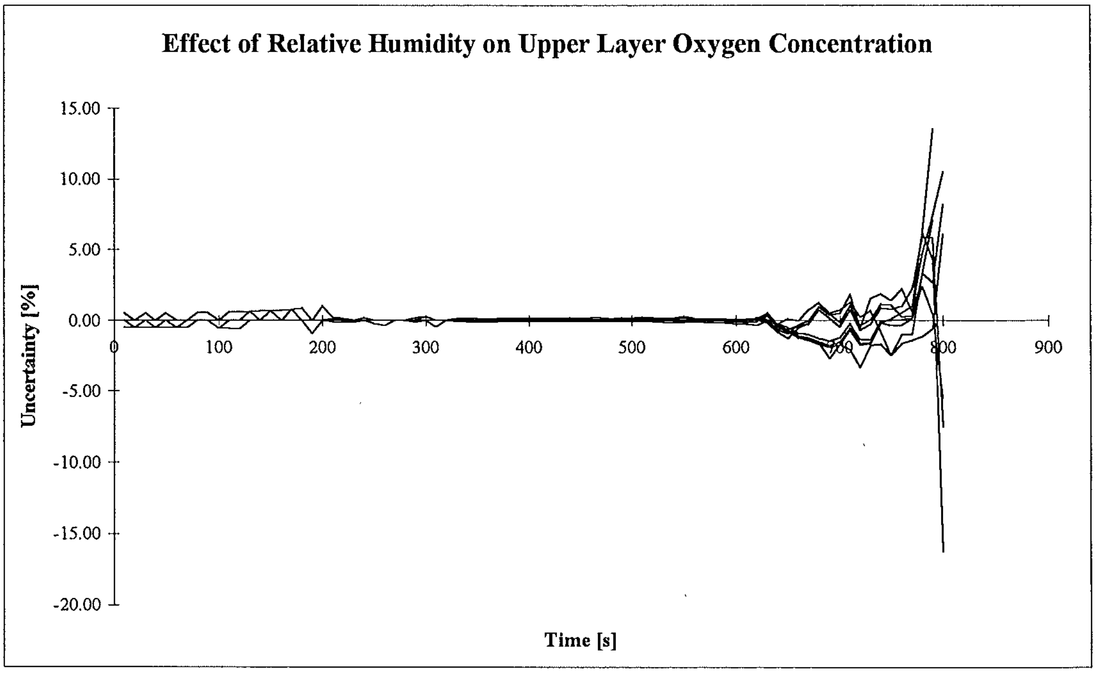


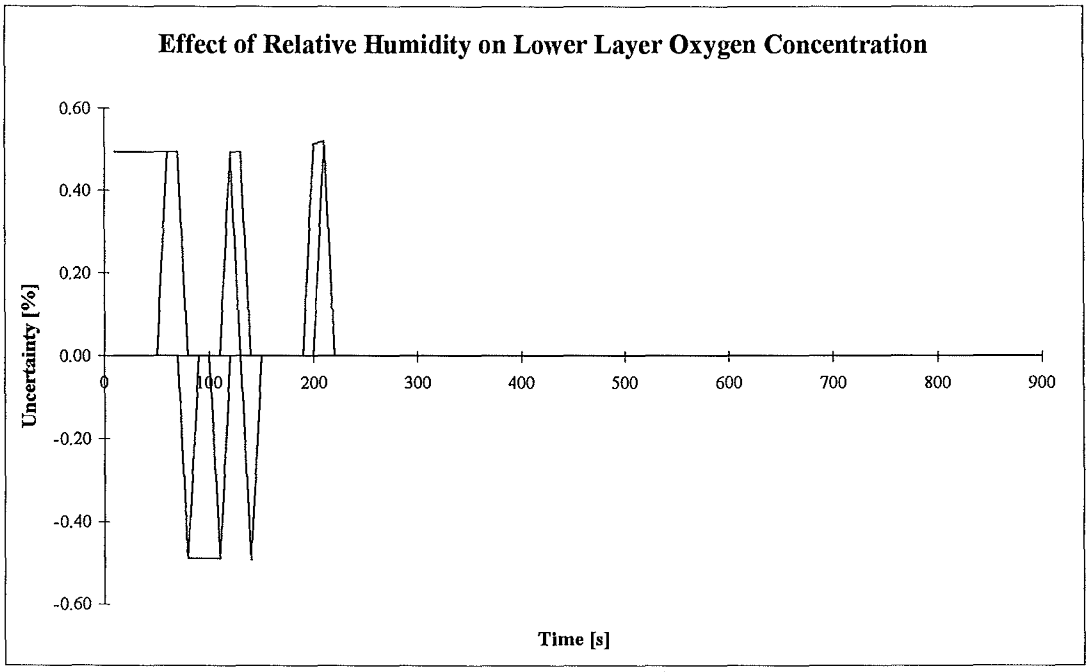
Effect of Relative Humidity on Vent Fire
Uncertainty [%]
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
0
100
200
300
400
500
600
700
800
900
Time [s]

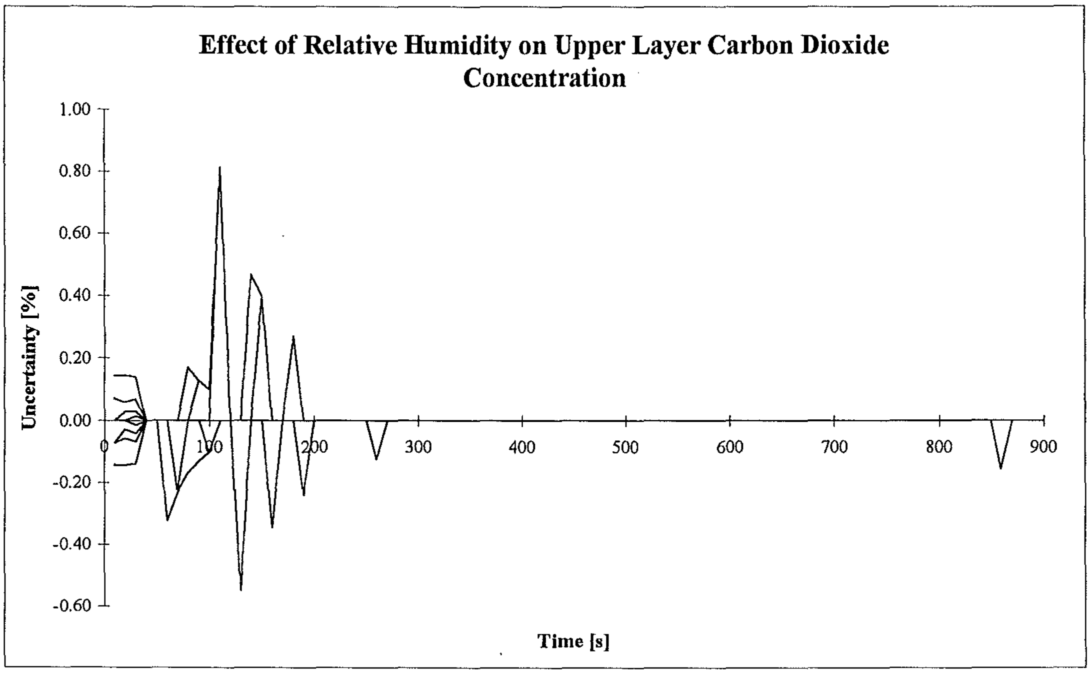


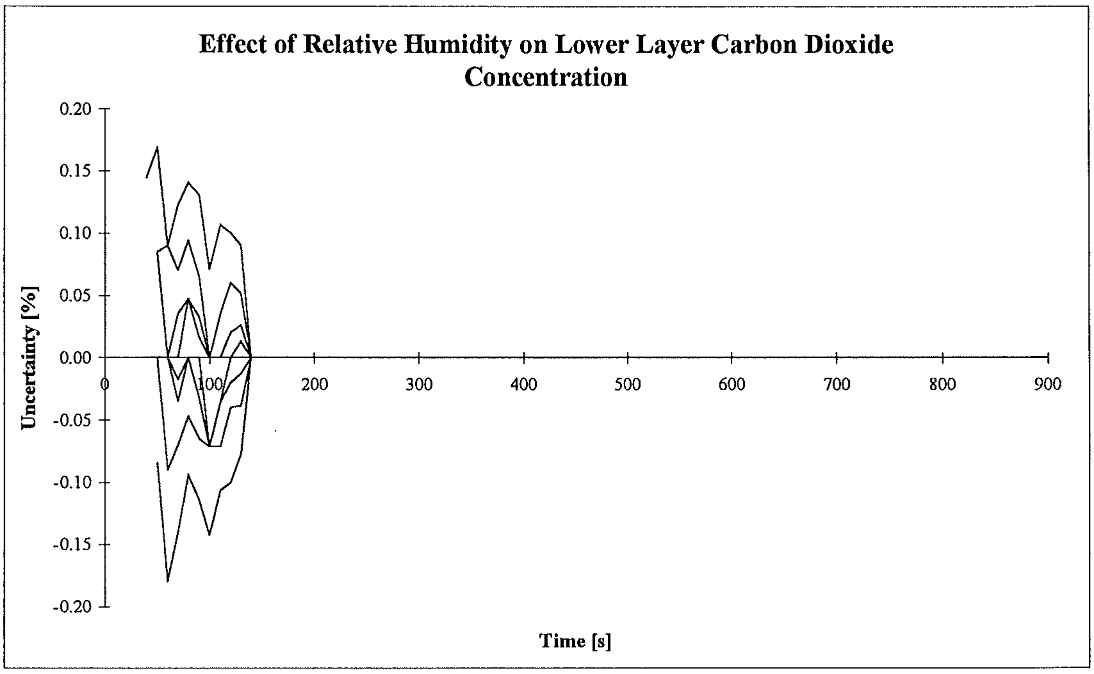
Effect of Relative Humidity on Radiation
Uncertainty [%]
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Relative Humidity on Convection
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

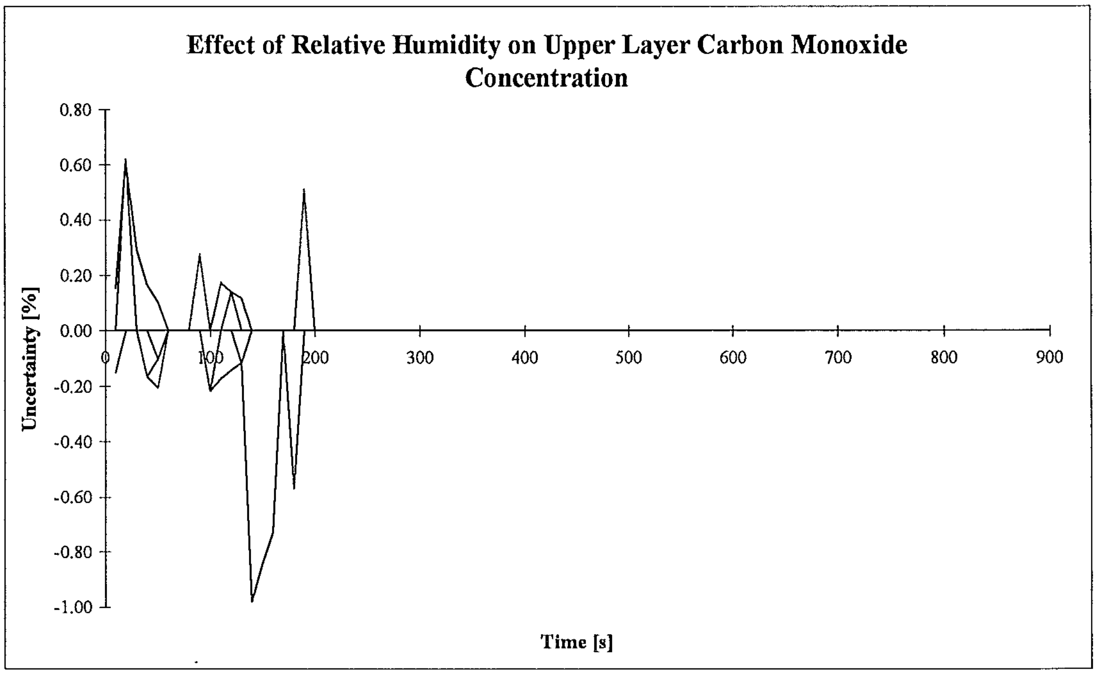

Effect of Relative Humidity on Upper Layer Oxygen Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Relative Humidity on Lower Layer Oxygen Concentration
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

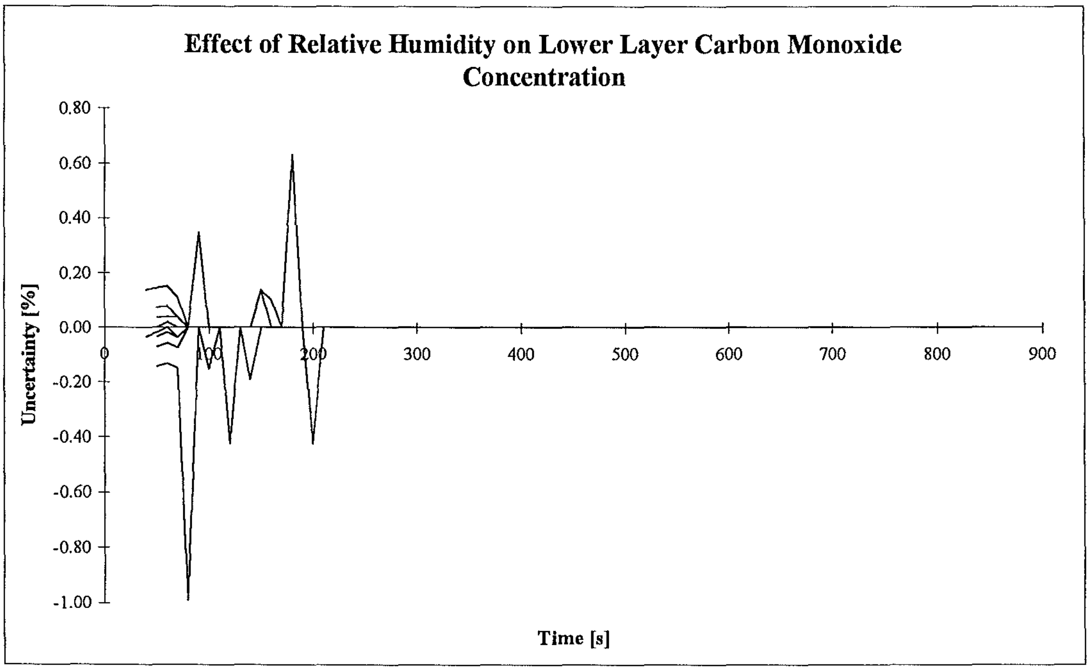

Effect of Relative Humidity on Upper Layer Carbon Dioxide Concentration
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



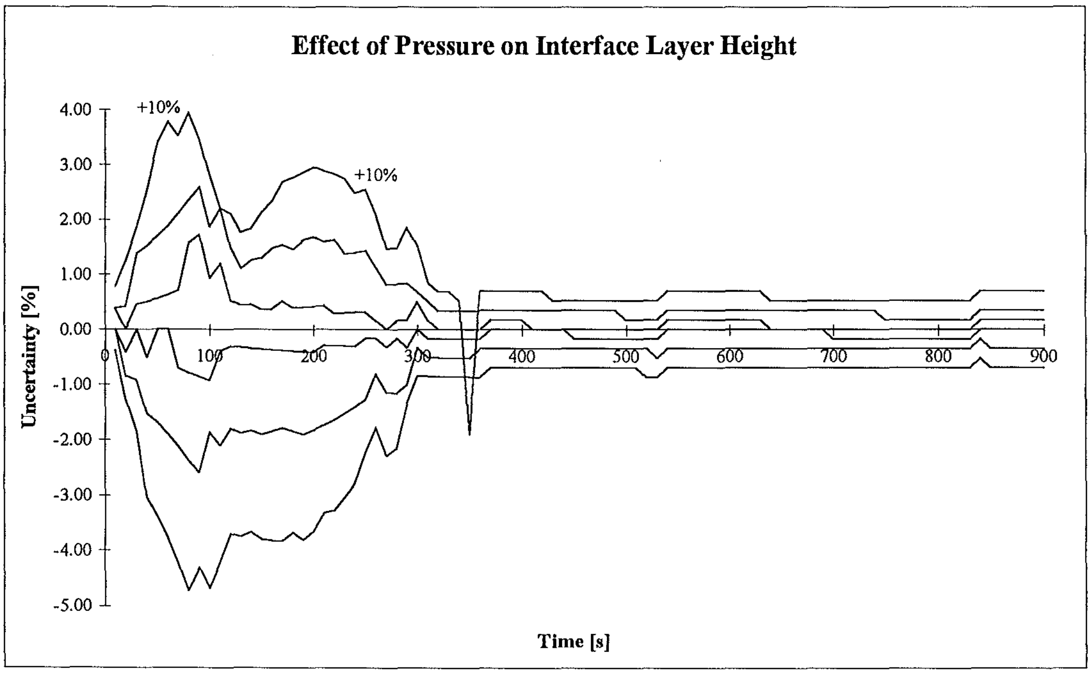
Effect of Relative Humidity on Lower Layer Carbon Dioxide Concentration
Uncertainty [%]
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
0
100
200
300
400
500
600
700
800
900
Time [s]



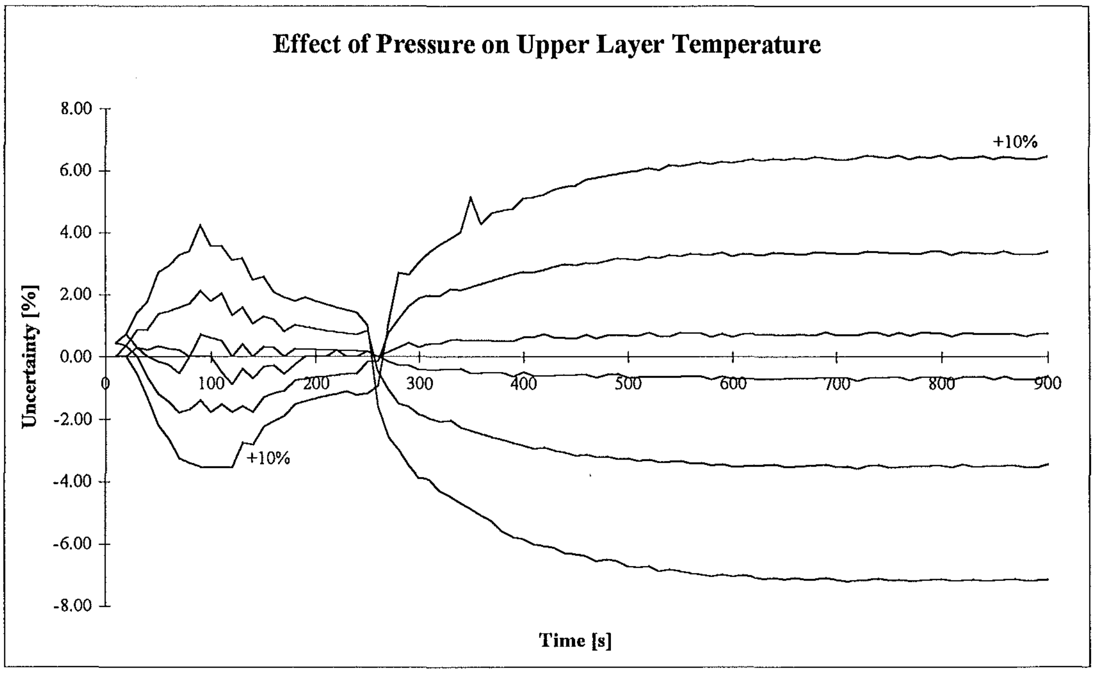
Effect of Relative Humidity on Upper Layer Carbon Monoxide Concentration
Uncertainty [%]
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
0
100
200
300
400
500
600
700
800
900
Time [s]

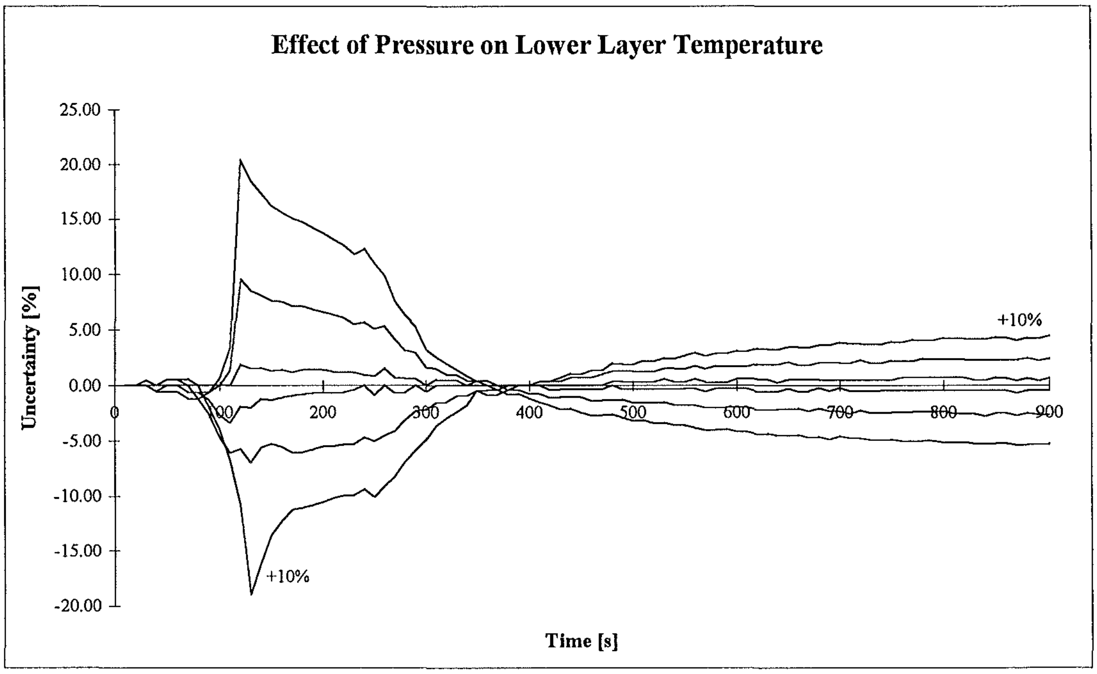


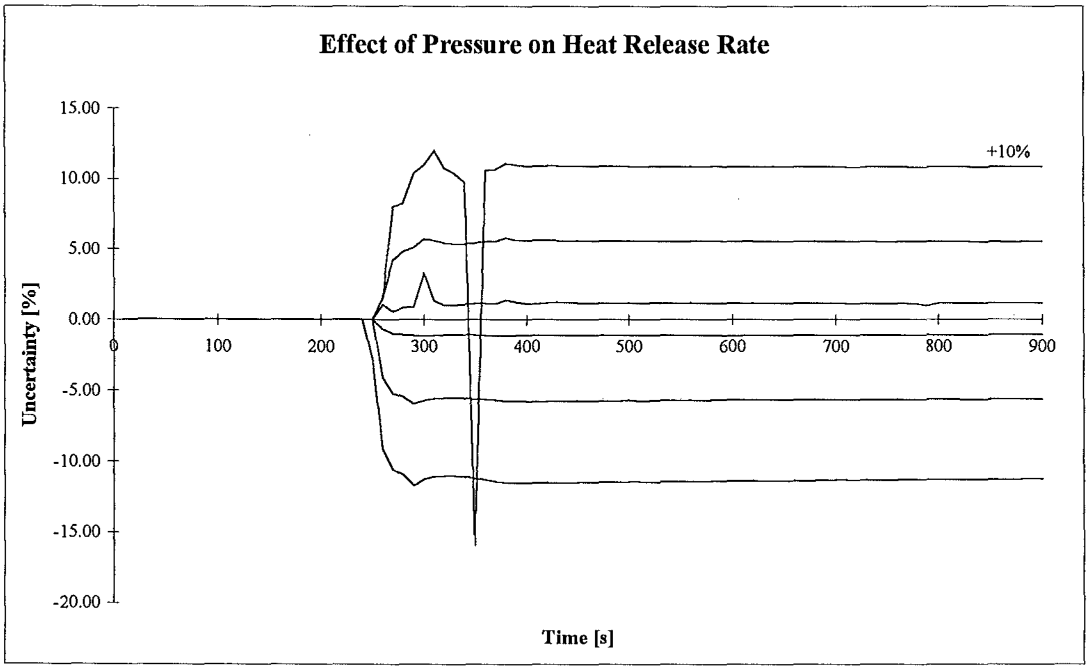
Effect of Relative Humidity on Lower Layer Carbon Monoxide Concentration
Uncertainty [%]
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
0
100
200
300
400
500
600
700
800
900
Time [s]

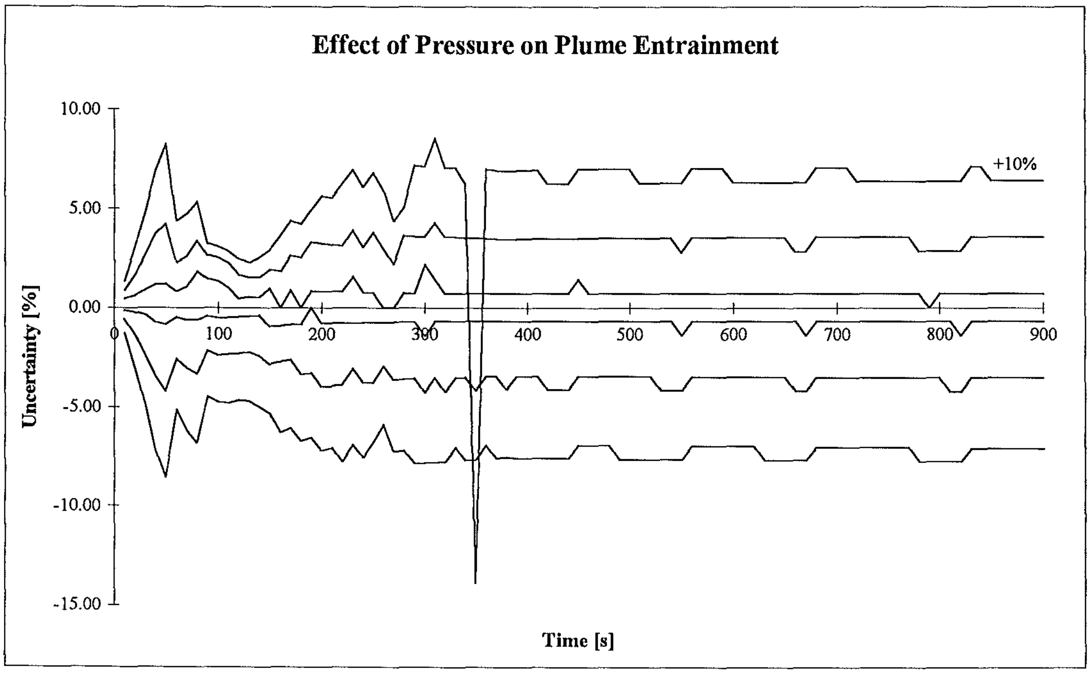


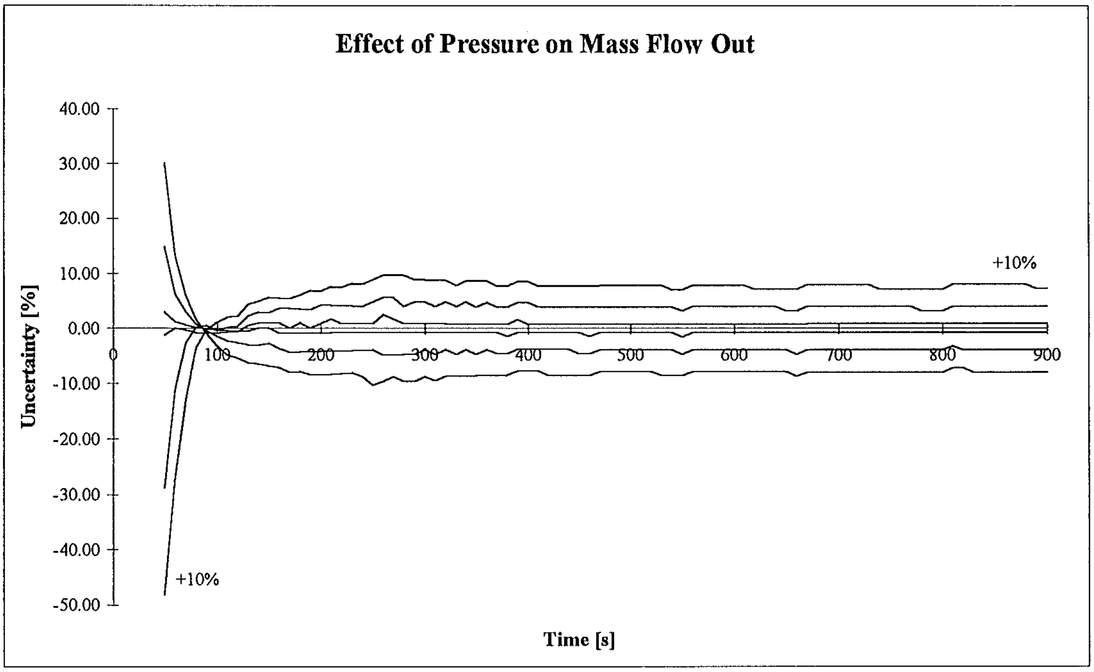
Effect of Pressure on Interface Layer Height
Uncertainty [%]
+10%
+10%
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0
100
200
300
400
500
600
700
800
900
Time [s]

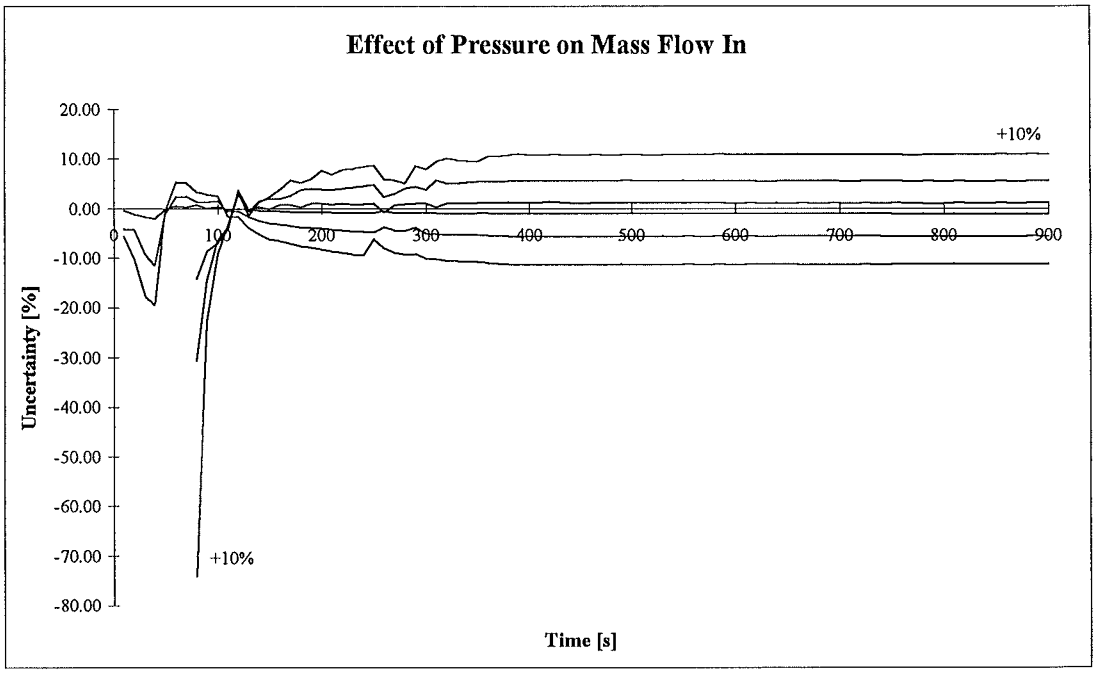

Effect of Pressure on Upper Layer Temperature
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]

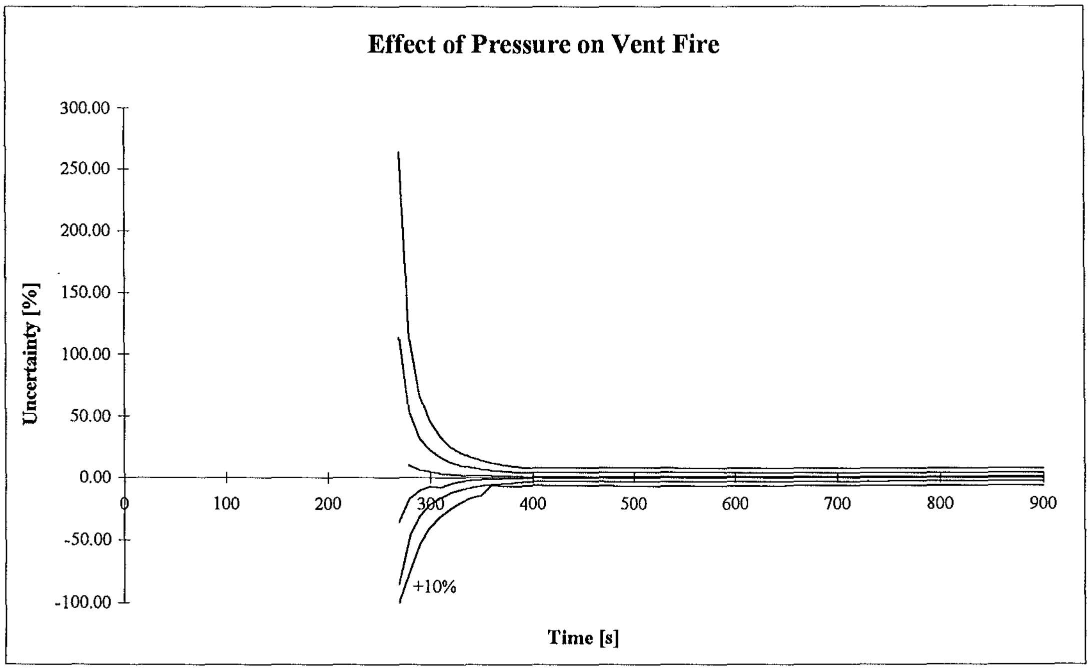

Effect of Pressure on Lower Layer Temperature
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]

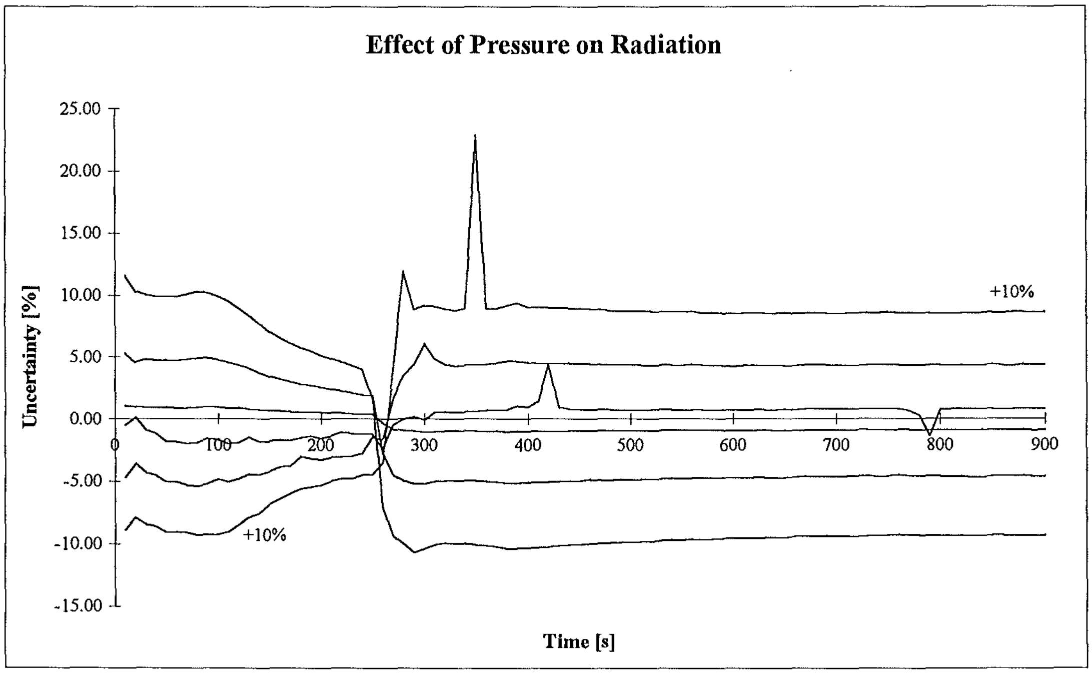

Effect of Pressure on Heat Release Rate
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

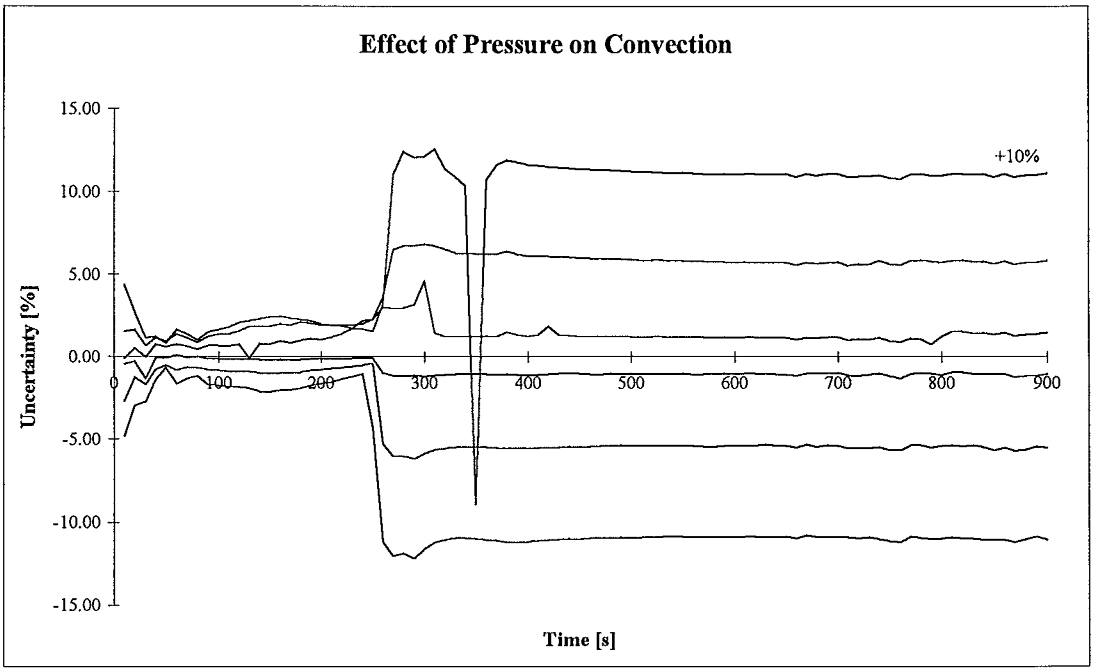

Effect of Pressure on Plume Entrainment
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

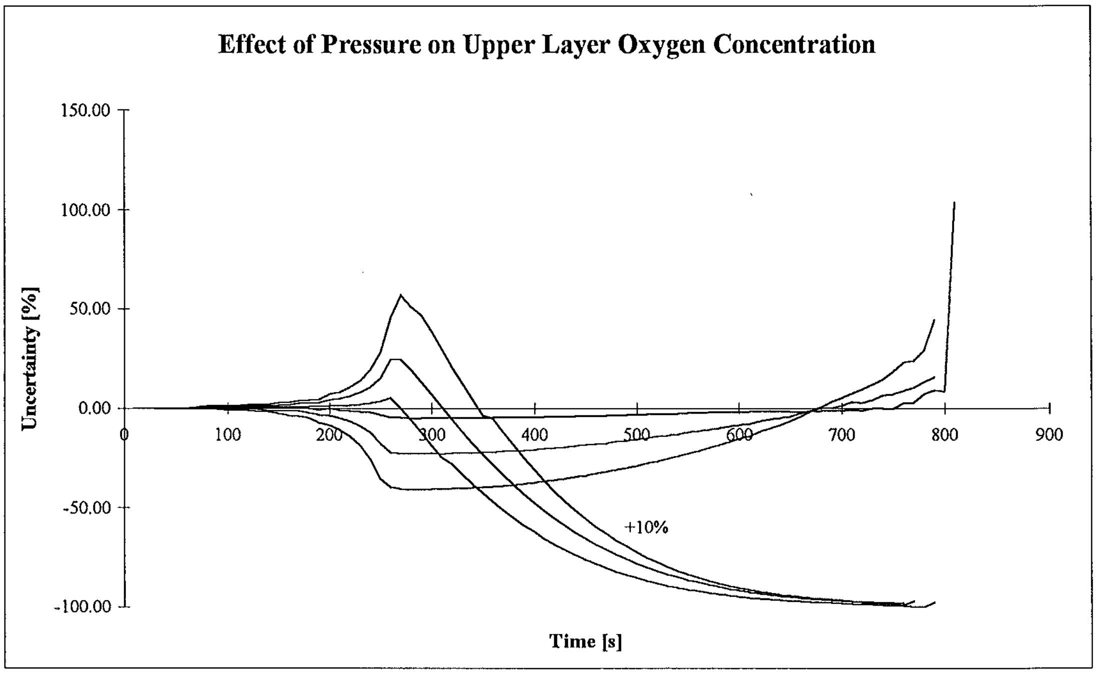

Effect of Pressure on Mass Flow Out
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]

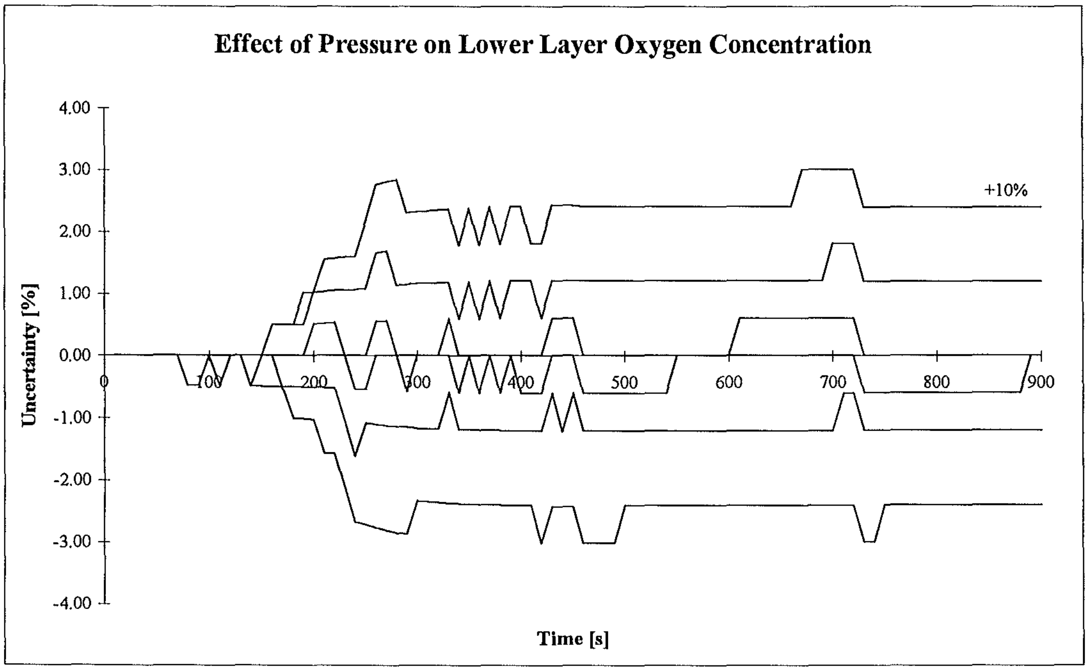

Effect of Pressure on Mass Flow In
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]


Effect of Pressure on Vent Fire
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

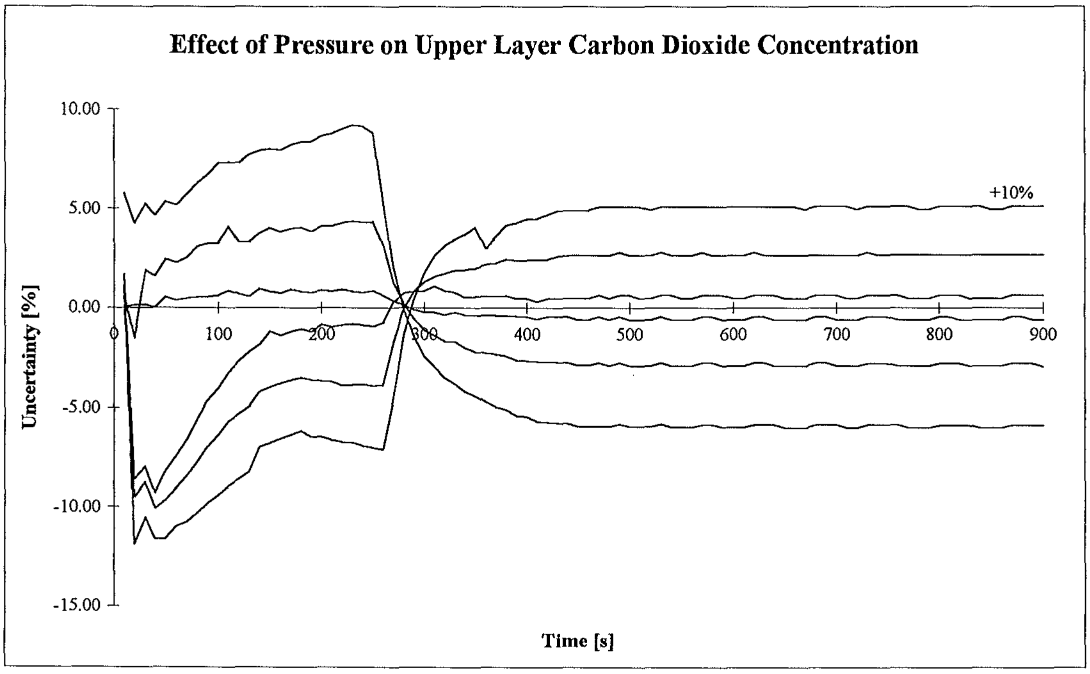

Effect of Pressure on Radiation
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]


Effect of Pressure on Convection
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

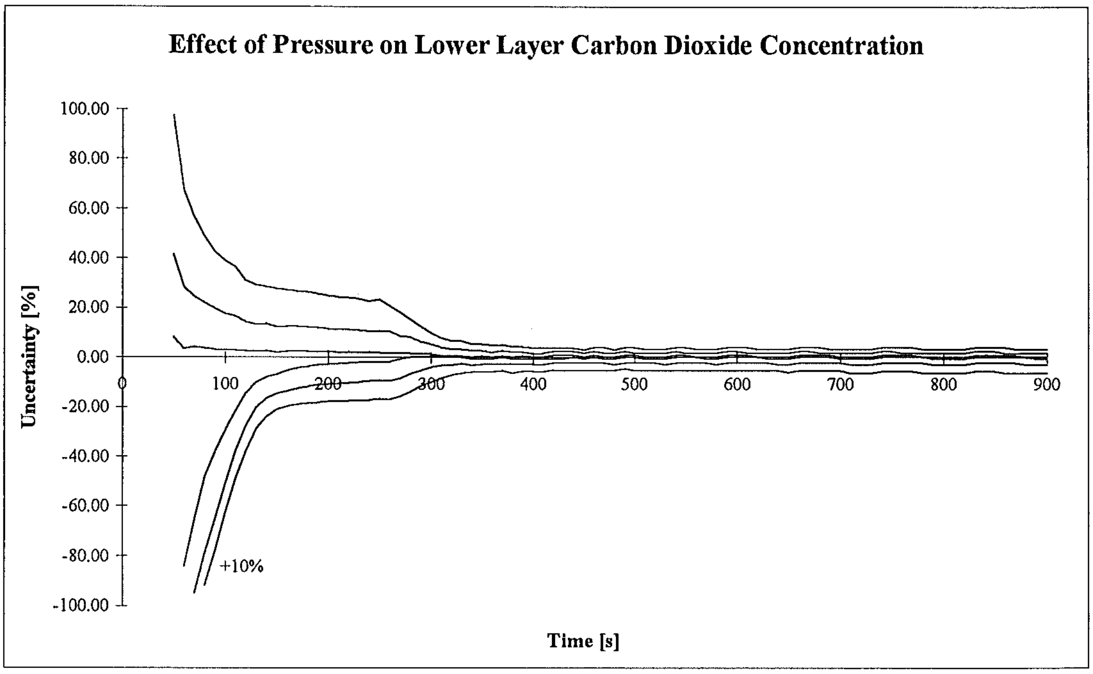

Effect of Pressure on Upper Layer Oxygen Concentration
150.00
100.00
50.00
0.00
-50.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

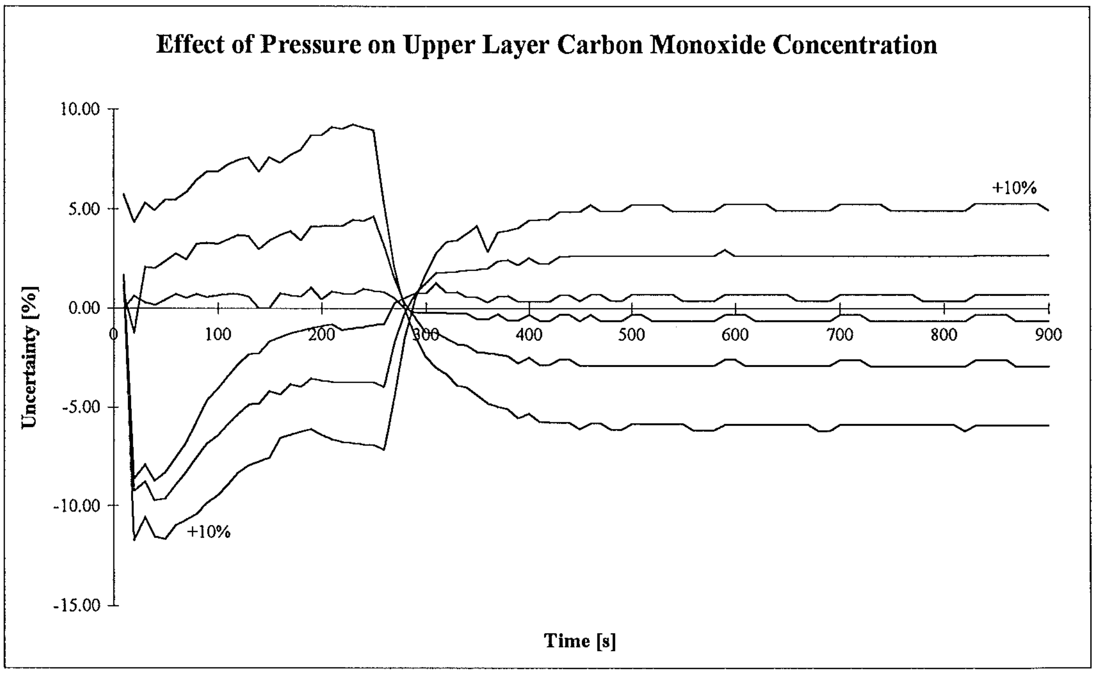


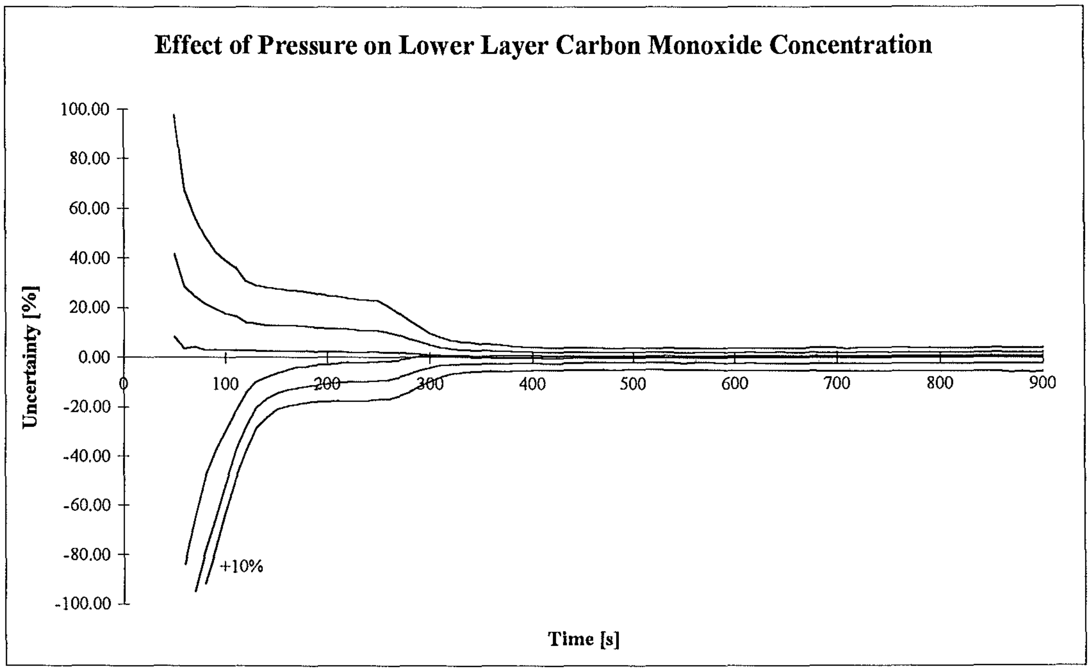
Effect of Pressure on Lower Layer Oxygen Concentration
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

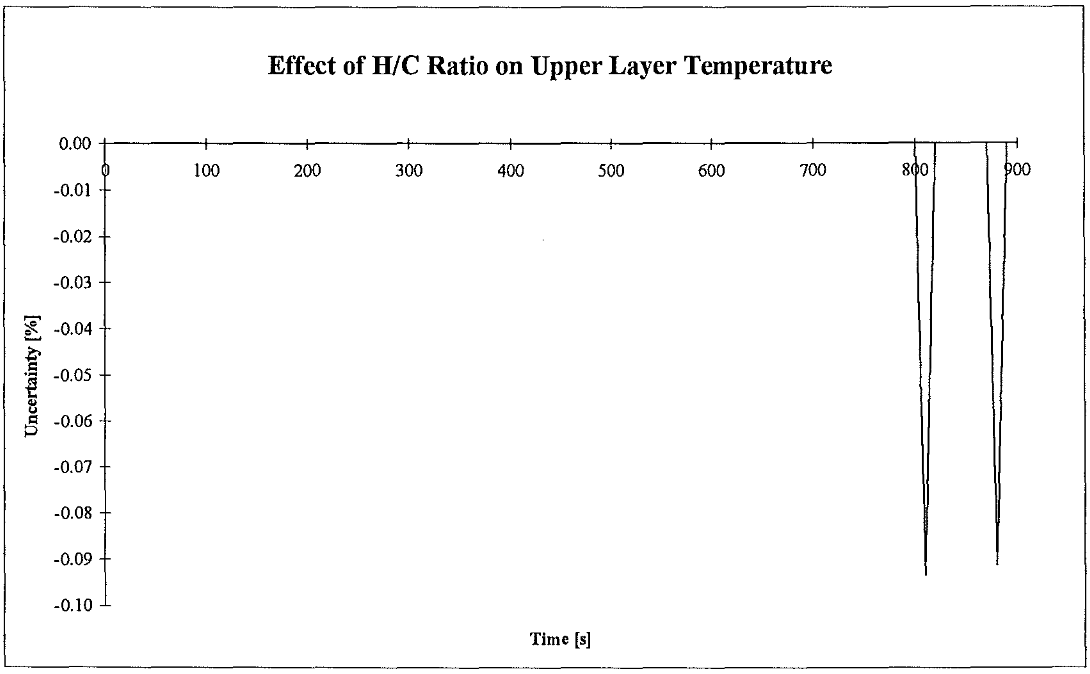


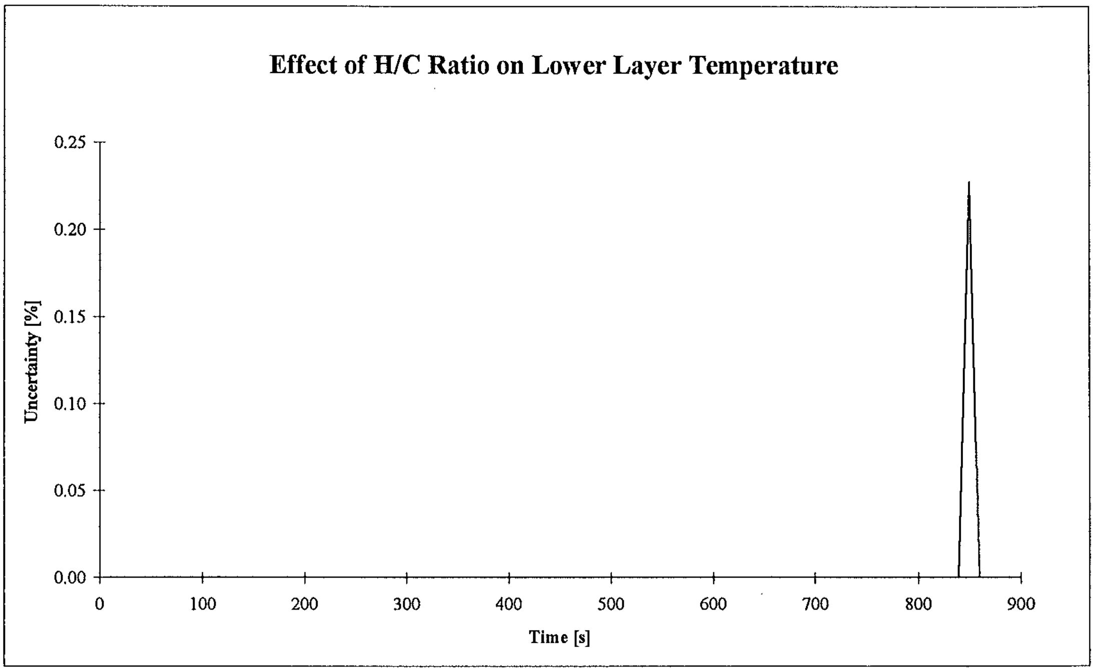
Effect of Pressure on Upper Layer Carbon Dioxide Concentration
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]


Effect of Pressure on Lower Layer Carbon Dioxide Concentration
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

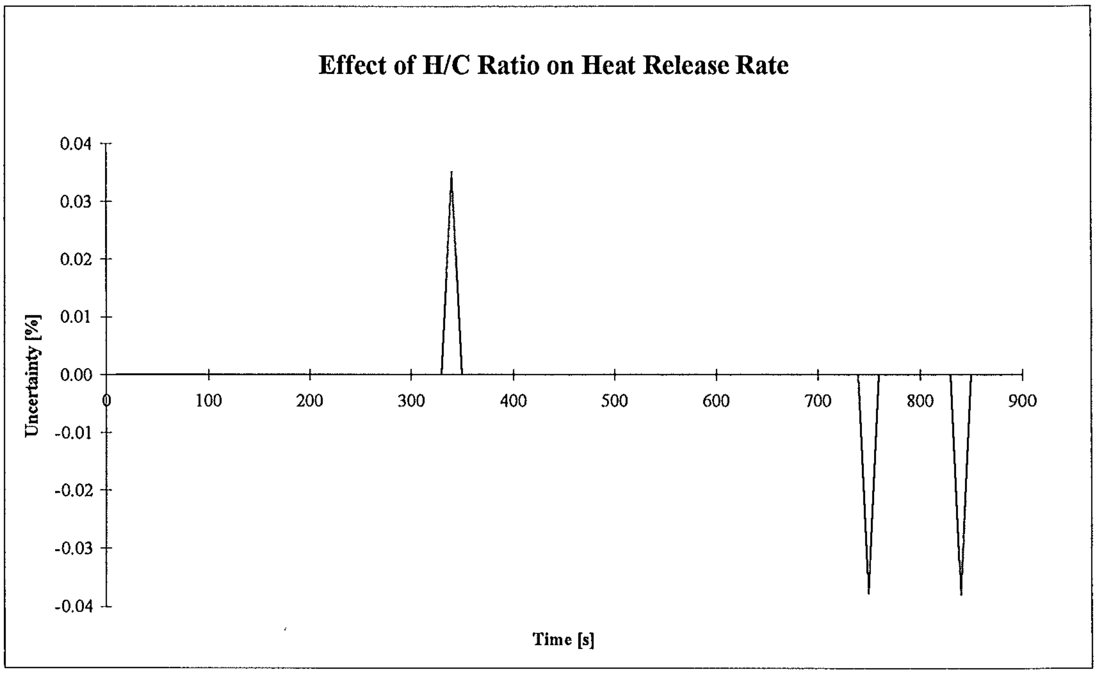

Effect of Pressure on Upper Layer Carbon Monoxide Concentration
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
+10%
Time [s]


Effect of Pressure on Lower Layer Carbon Monoxide Concentration
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+10%
Time [s]

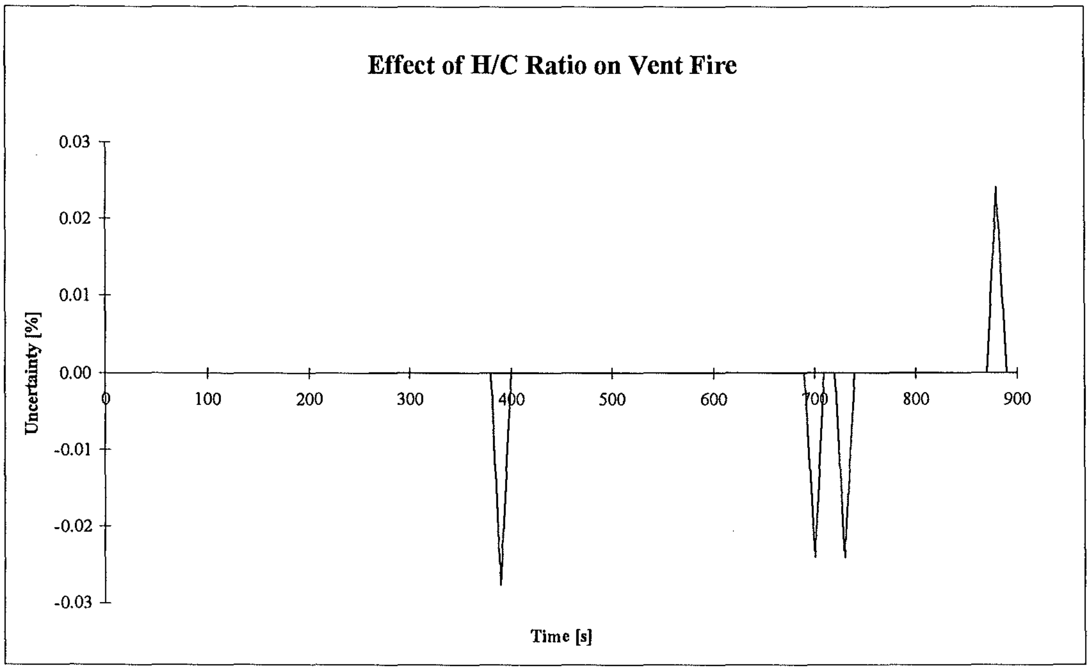

Effect of H/C Ratio on Upper Layer Temperature
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

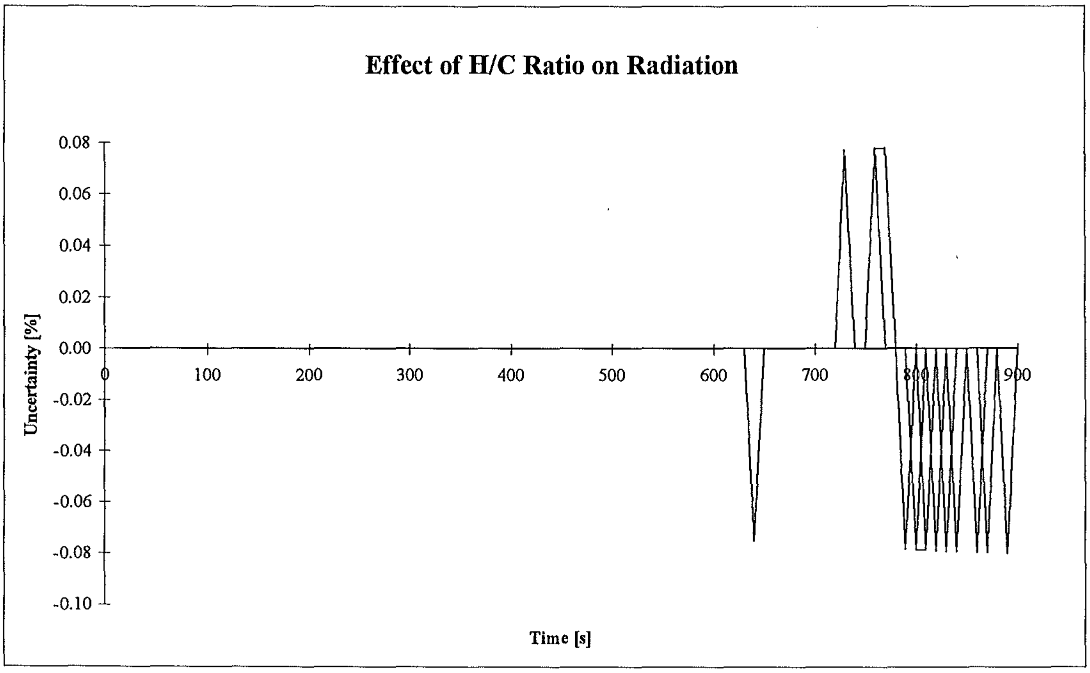


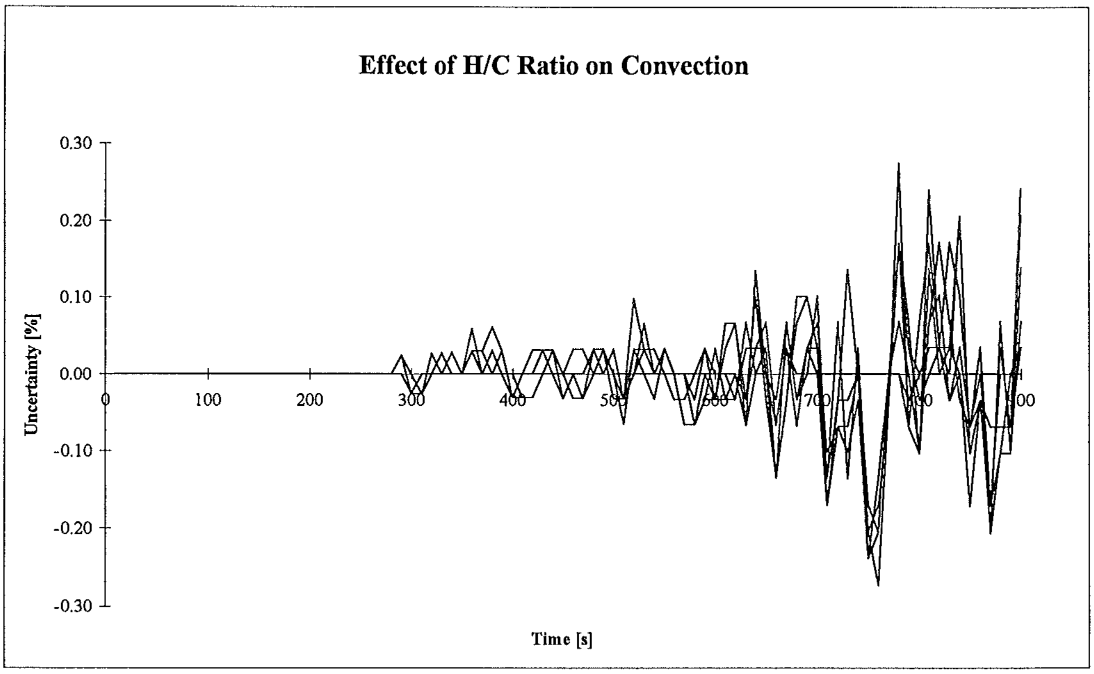
Effect of H/C Ratio on Lower Layer Temperature
Uncertainty [%]
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
500
600
700
800
900
Time [s]

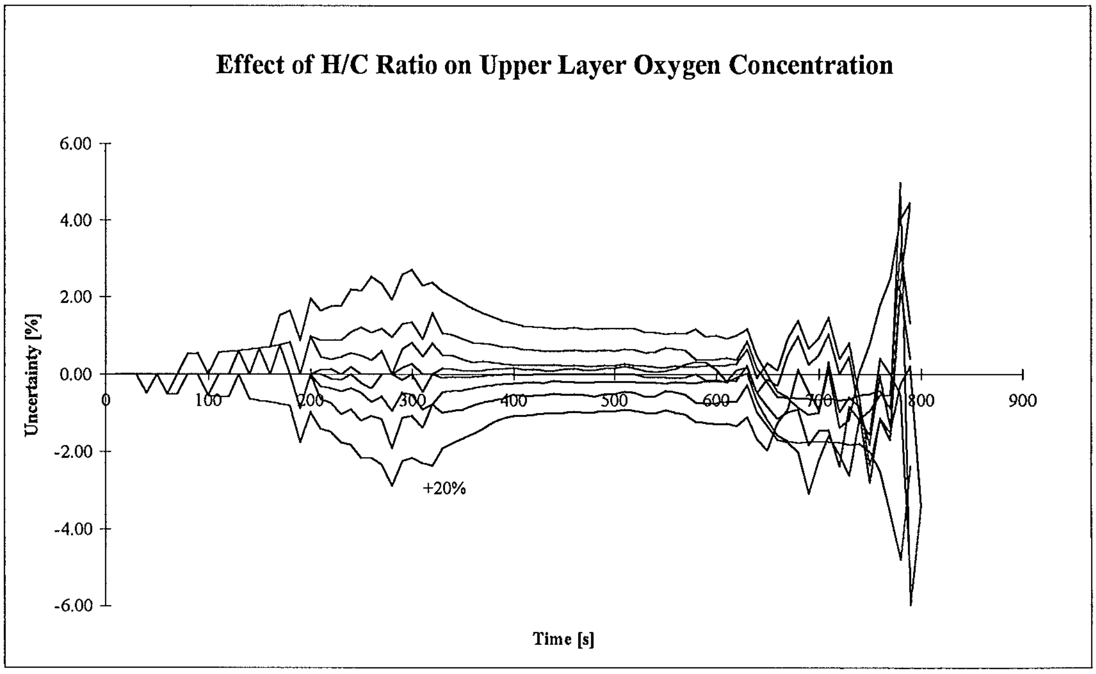


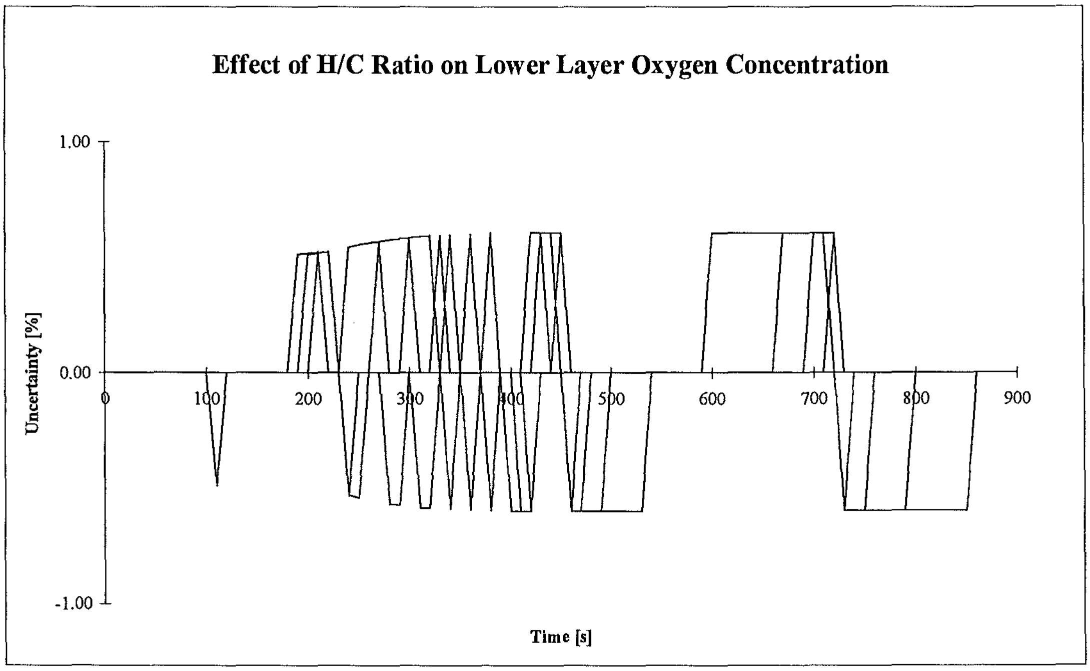
Effect of H/C Ratio on Heat Release Rate
Uncertainty [%]
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of H/C Ratio on Vent Fire
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

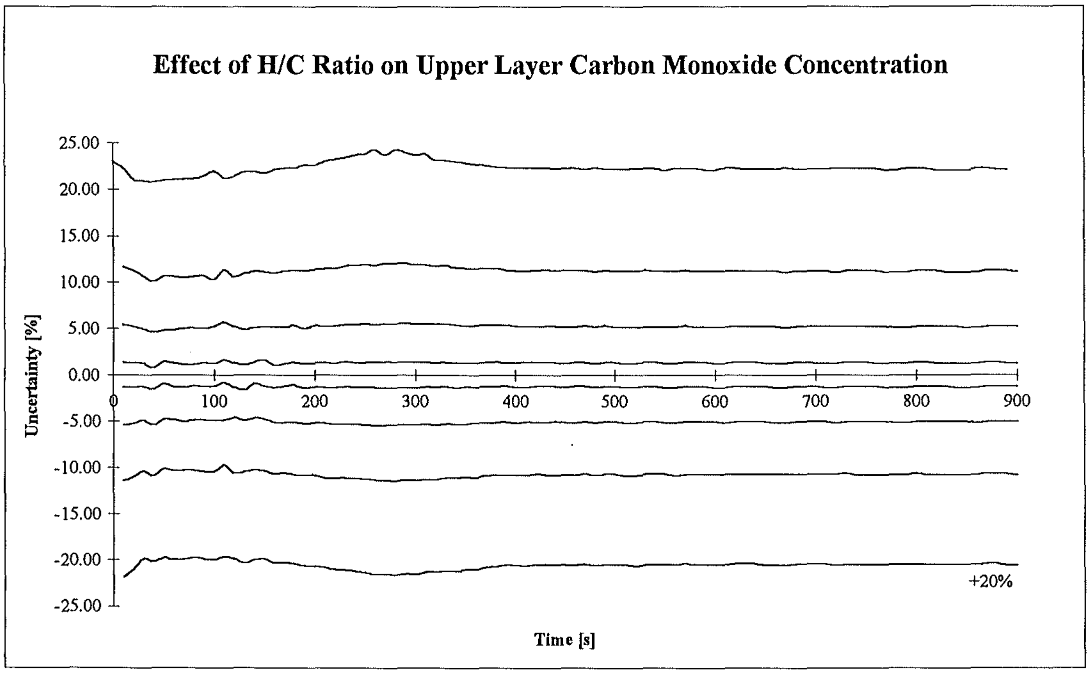

Effect of H/C Ratio on Radiation
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of H/C Ratio on Convection
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
Uncertainty [%]
100
200
Time [s]

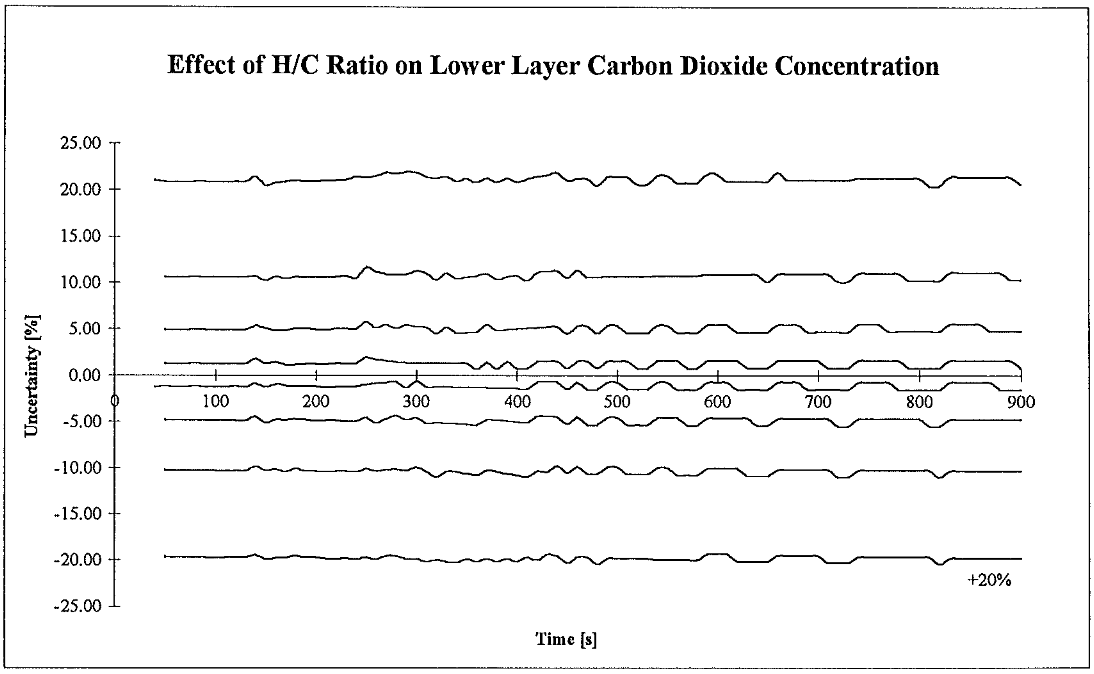

Effect of H/C Ratio on Upper Layer Oxygen Concentration
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
Uncertainty [%]
900
+20%
Time [s]

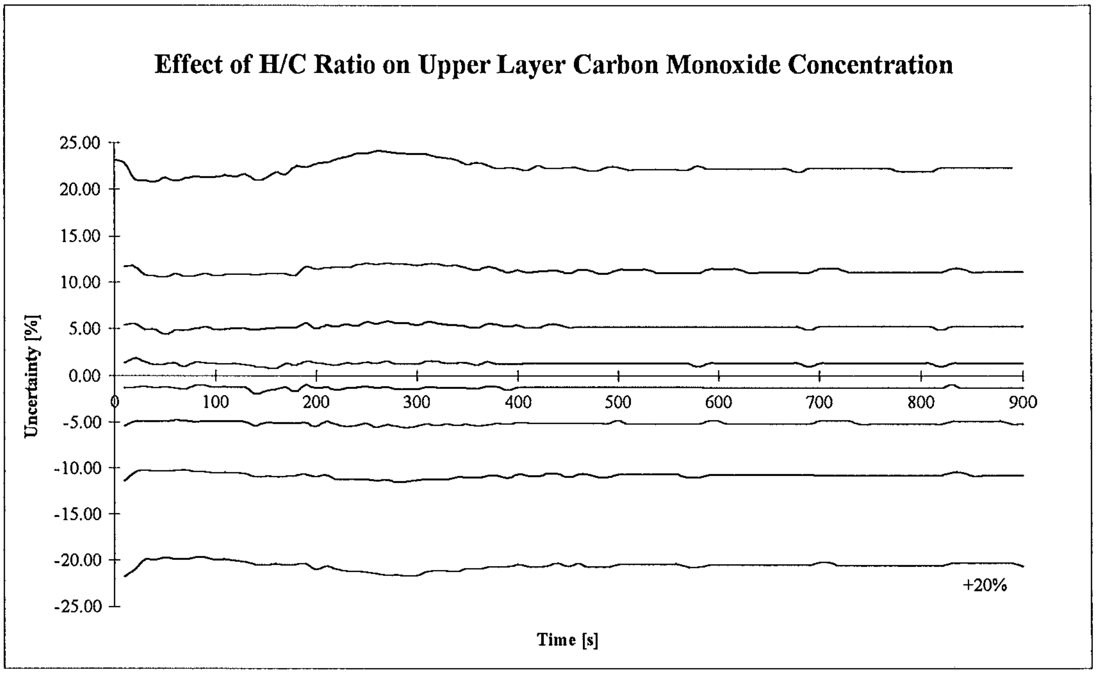


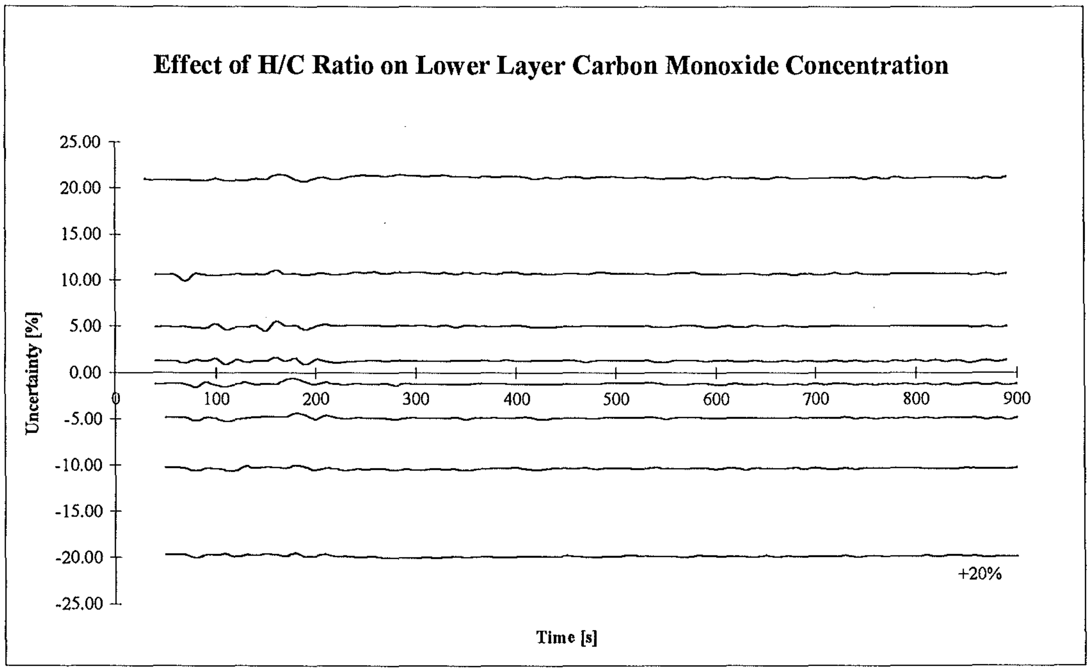
Effect of H/C Ratio on Lower Layer Oxygen Concentration
1.00
0.00
-1.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



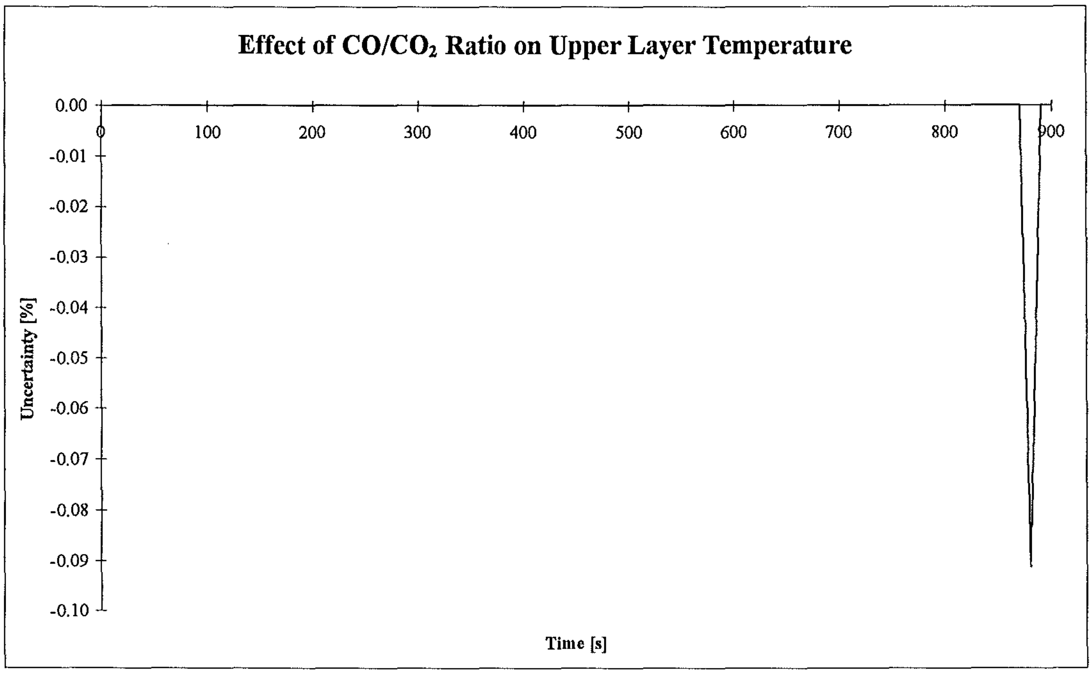
Effect of H/C Ratio on Upper Layer Carbon Monoxide Concentration
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of H/C Ratio on Lower Layer Carbon Dioxide Concentration
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

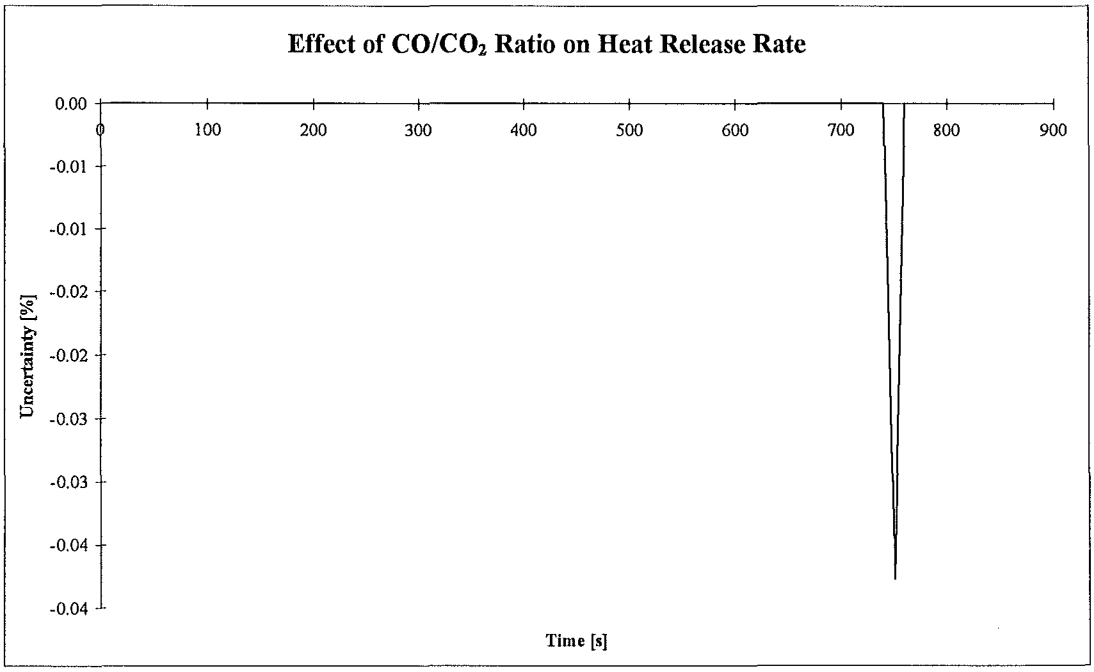

Effect of H/C Ratio on Upper Layer Carbon Monoxide Concentration
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



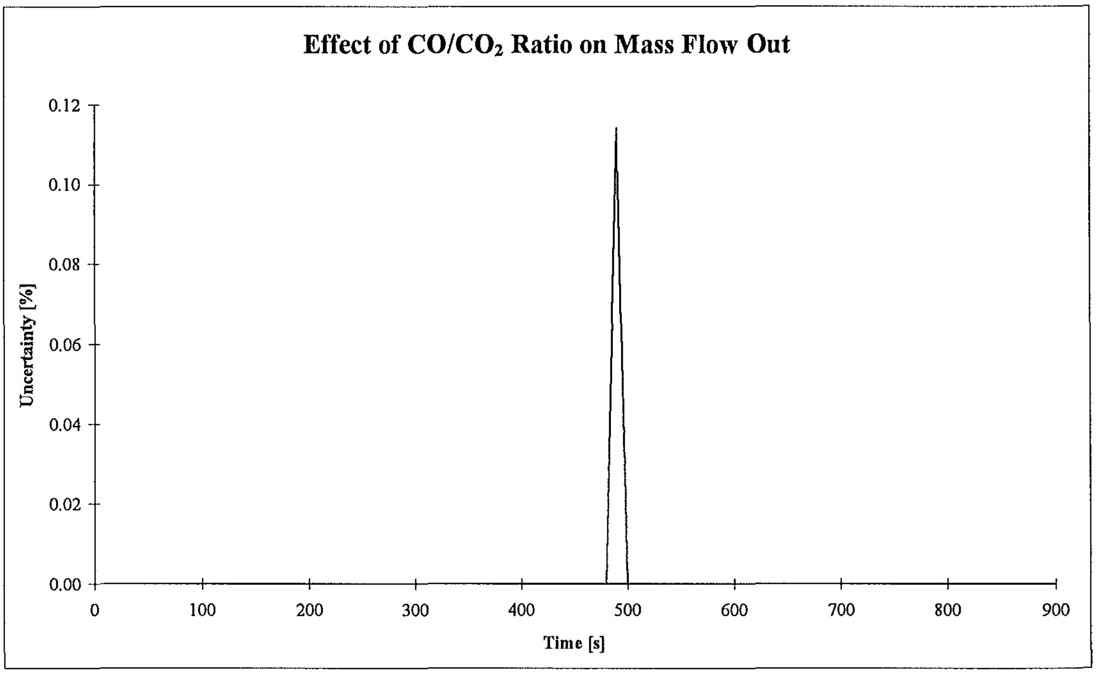
Effect of H/C Ratio on Lower Layer Carbon Monoxide Concentration
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



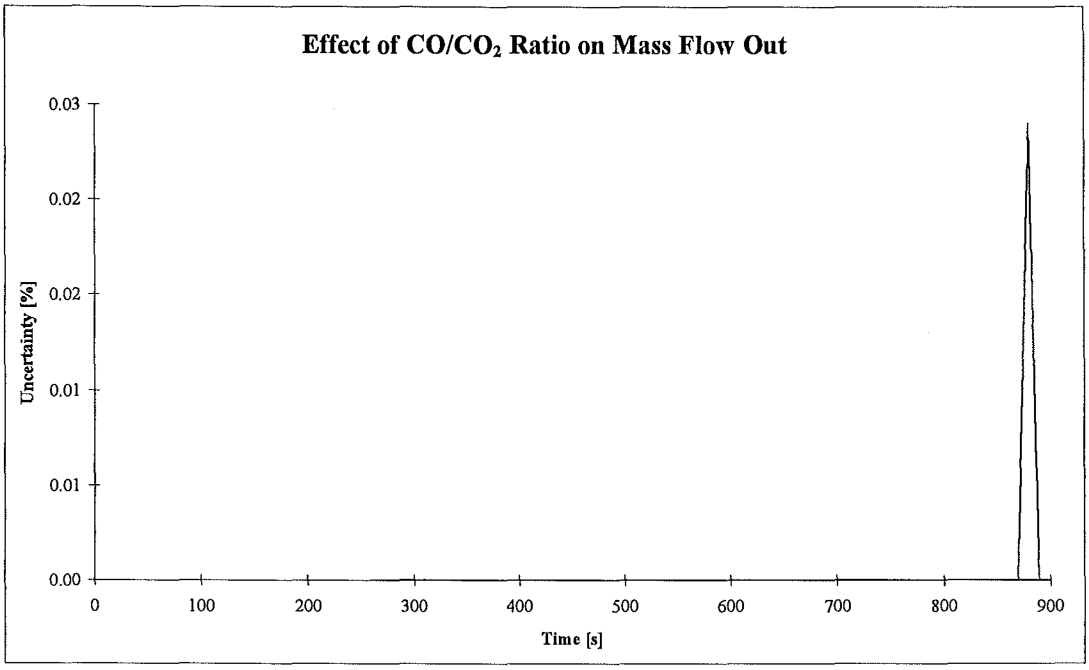
Effect of CO/CO2 Ratio on Upper Layer Temperature
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



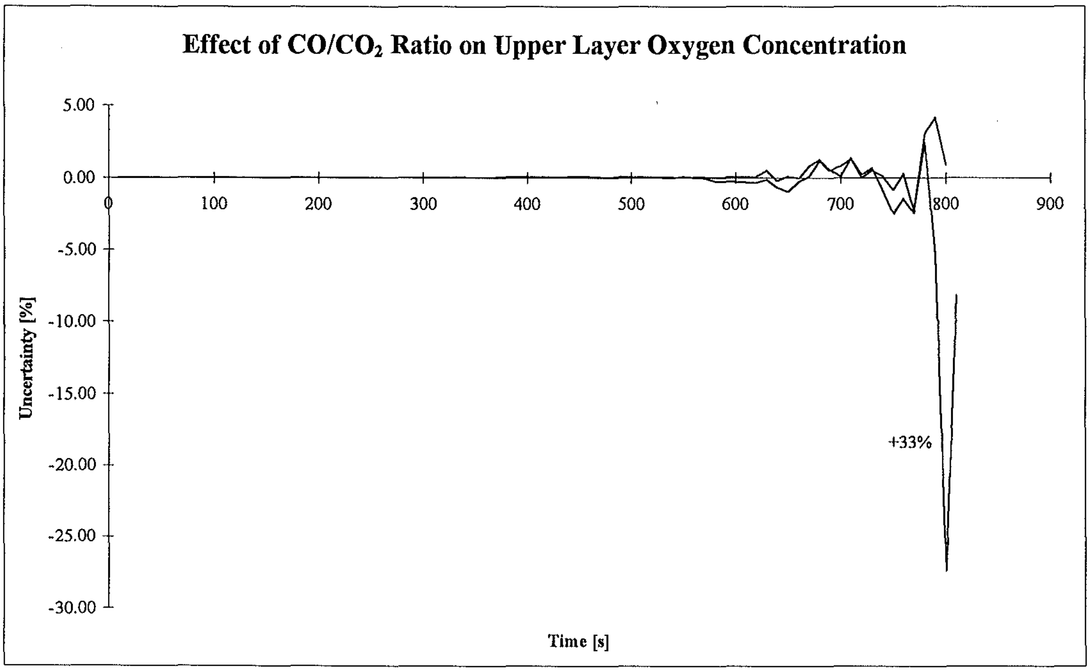
Effect of CO/CO_2 Ratio on Heat Release Rate
0.00
-0.01
-0.01
-0.02
-0.02
-0.03
-0.03
-0.04
-0.04
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



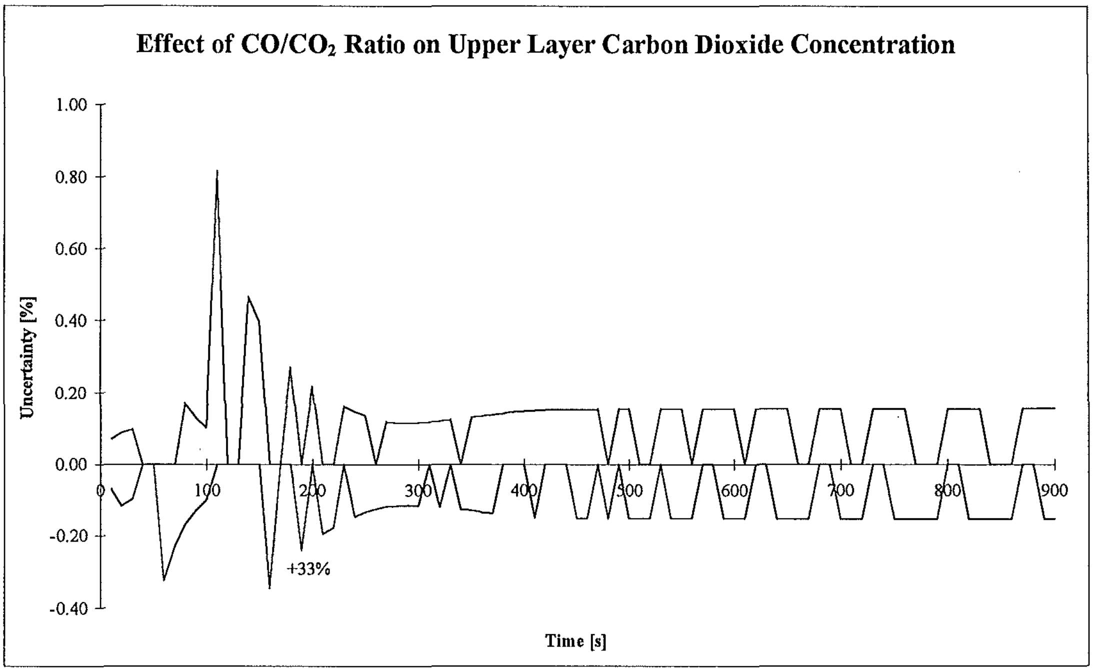
Effect of CO/CO_2 Ratio on Mass Flow Out
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

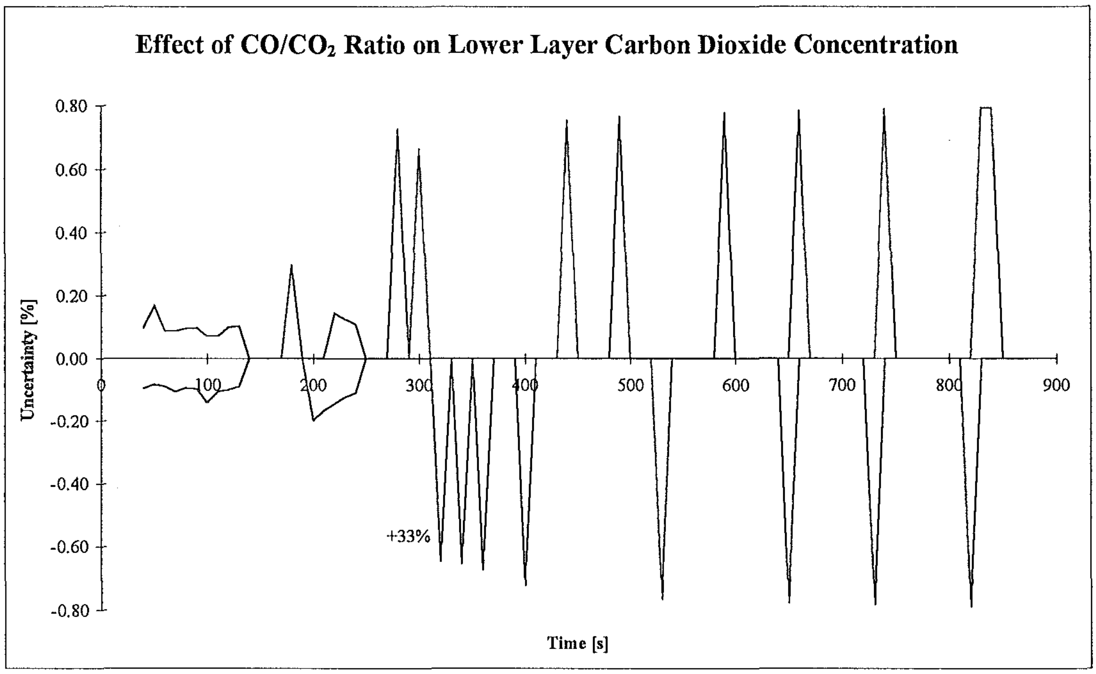


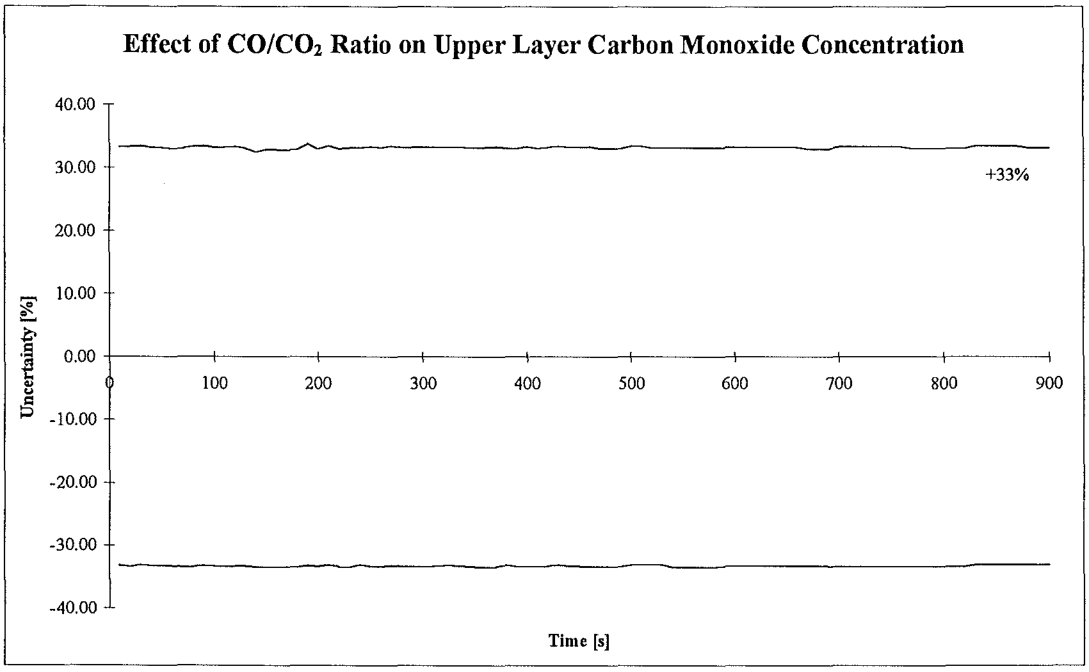
Effect of CO/CO_2 Ratio on Mass Flow Out
0.03
0.02
0.02
0.01
0.01
0.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

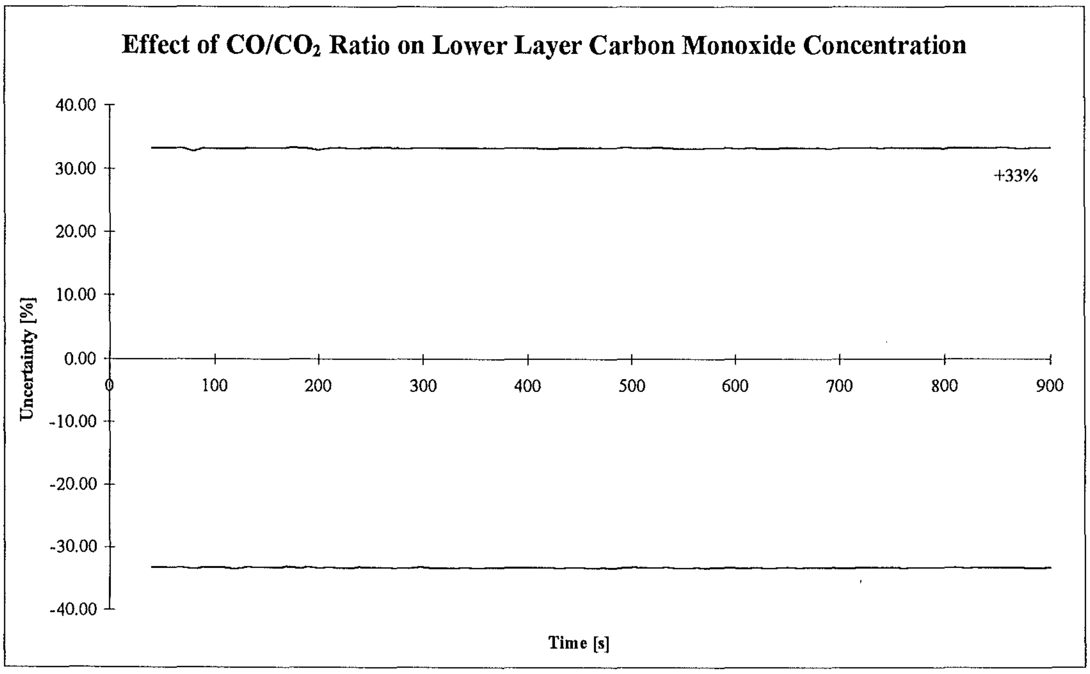


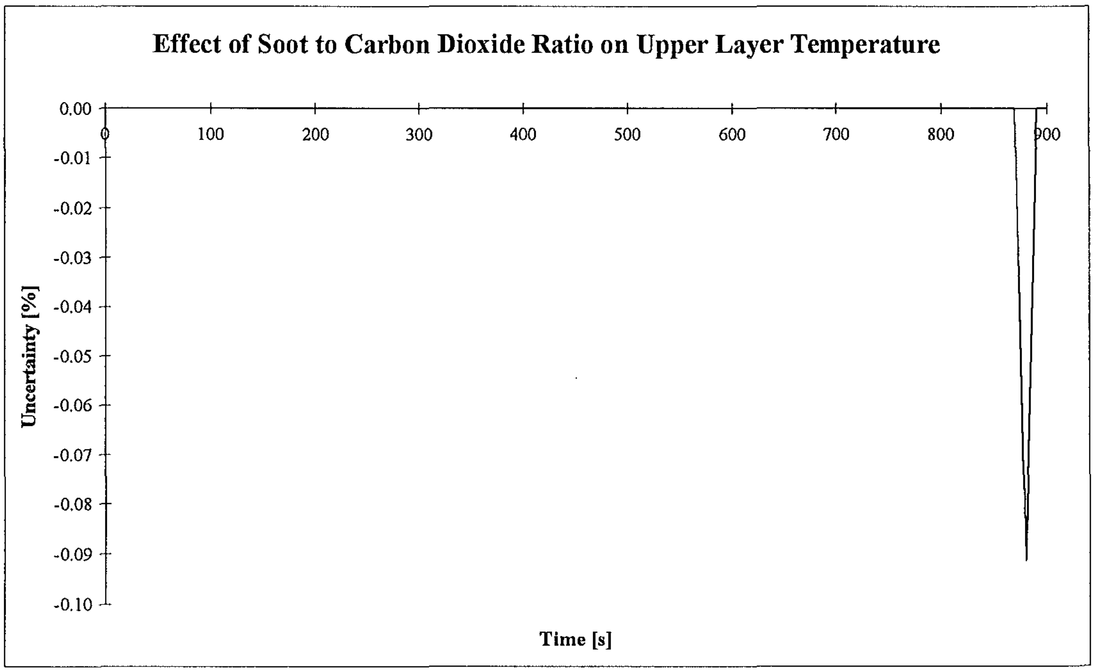
Effect of CO/CO_2 Ratio on Upper Layer Oxygen Concentration
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+33%
Time [s]


Effect of CO/CO₂ Ratio on Upper Layer Carbon Dioxide Concentration
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+33%
Time [s]

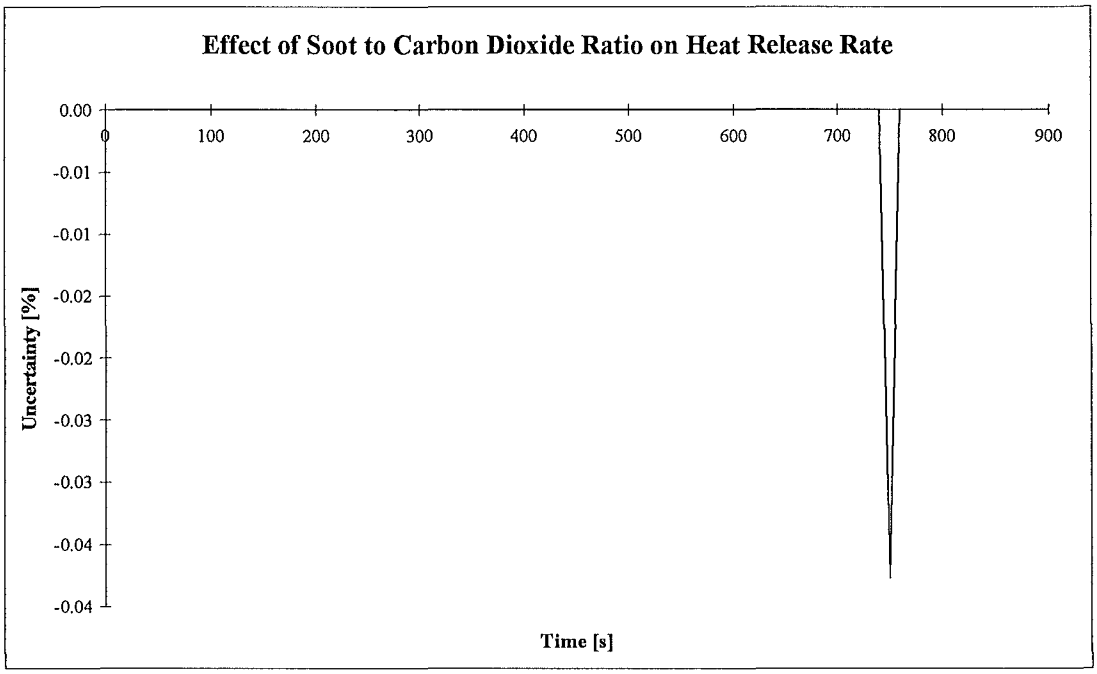

Effect of CO/CO₂ Ratio on Lower Layer Carbon Dioxide Concentration
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+33%
Time [s]


Effect of CO/CO2 Ratio on Upper Layer Carbon Monoxide Concentration
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+33%
Time [s]

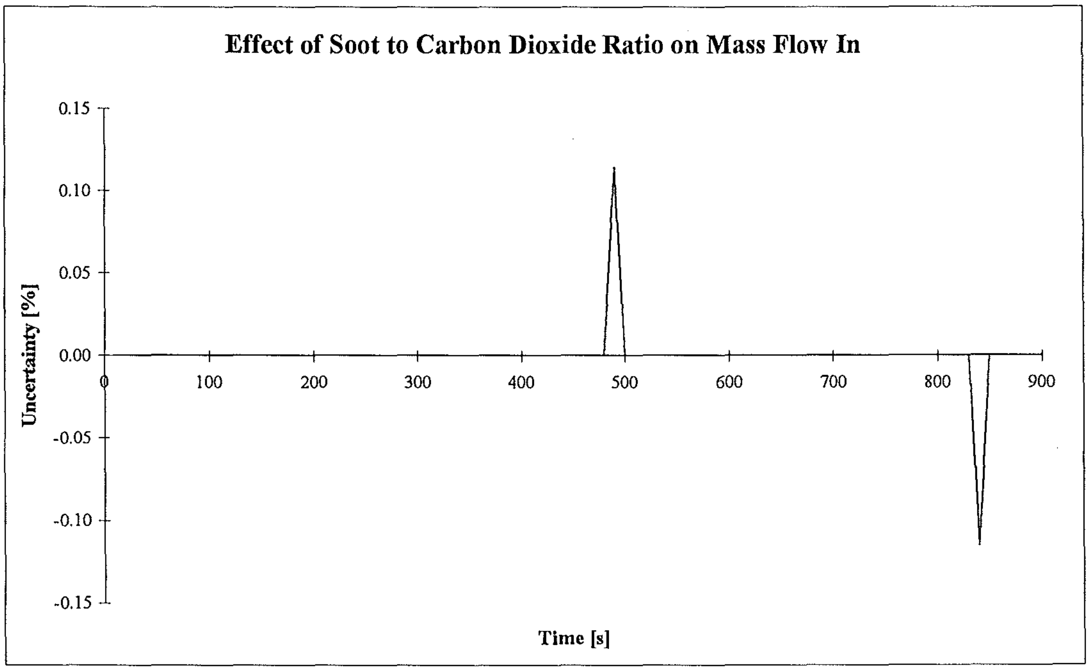

Effect of CO/CO2 Ratio on Lower Layer Carbon Monoxide Concentration
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+33%
Time [s]



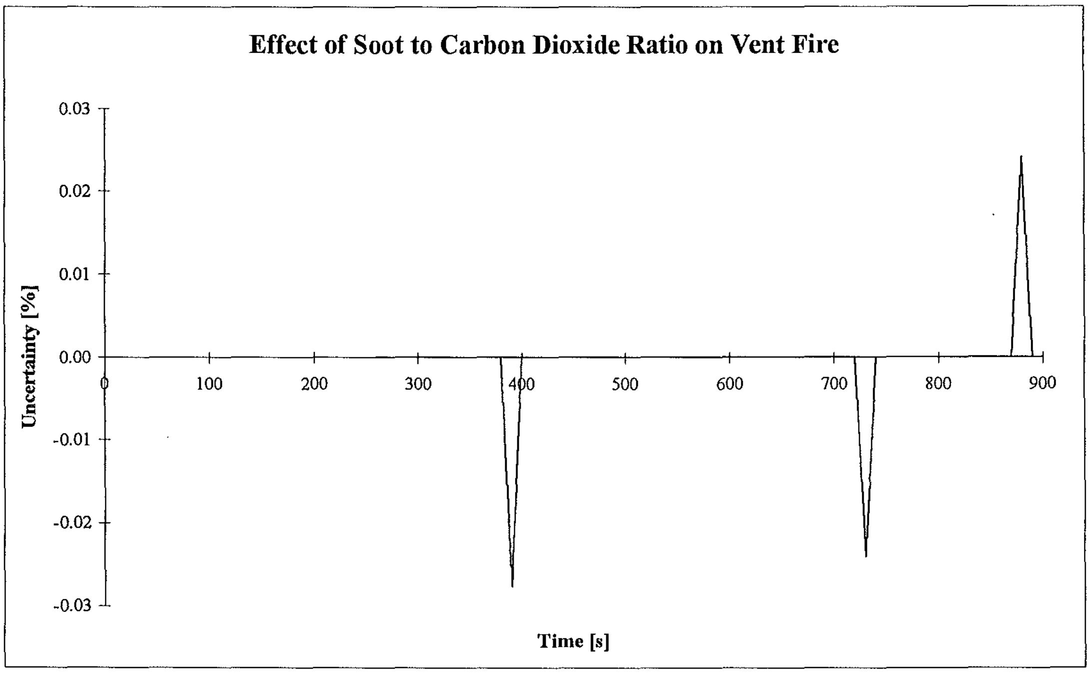
Effect of Soot to Carbon Dioxide Ratio on Upper Layer Temperature
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]



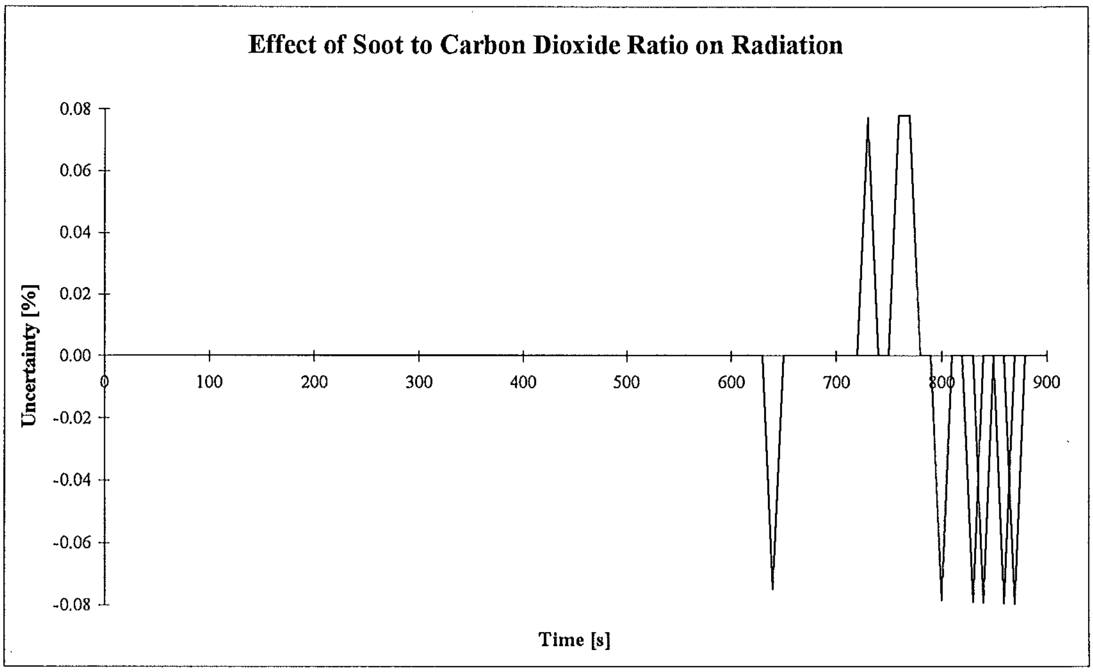
Effect of Soot to Carbon Dioxide Ratio on Heat Release Rate
0.00
-0.01
-0.01
-0.02
-0.02
-0.03
-0.03
-0.04
-0.04
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]

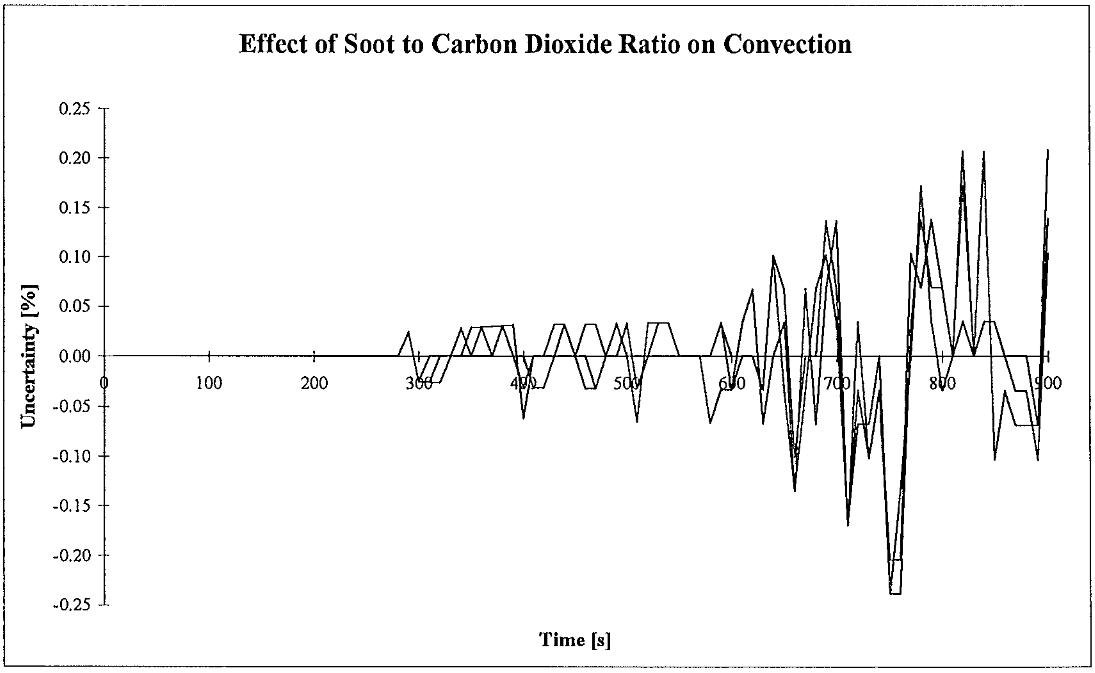


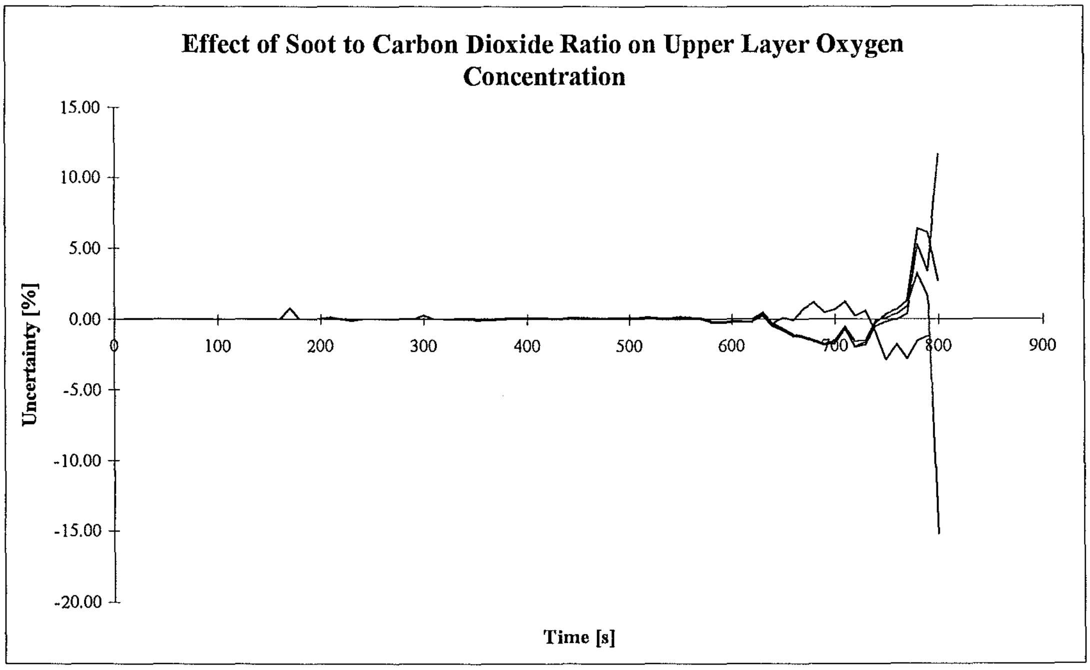
Effect of Soot to Carbon Dioxide Ratio on Mass Flow In
Uncertainty [%]
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0
100
200
300
400
500
600
700
800
900
Time [s]



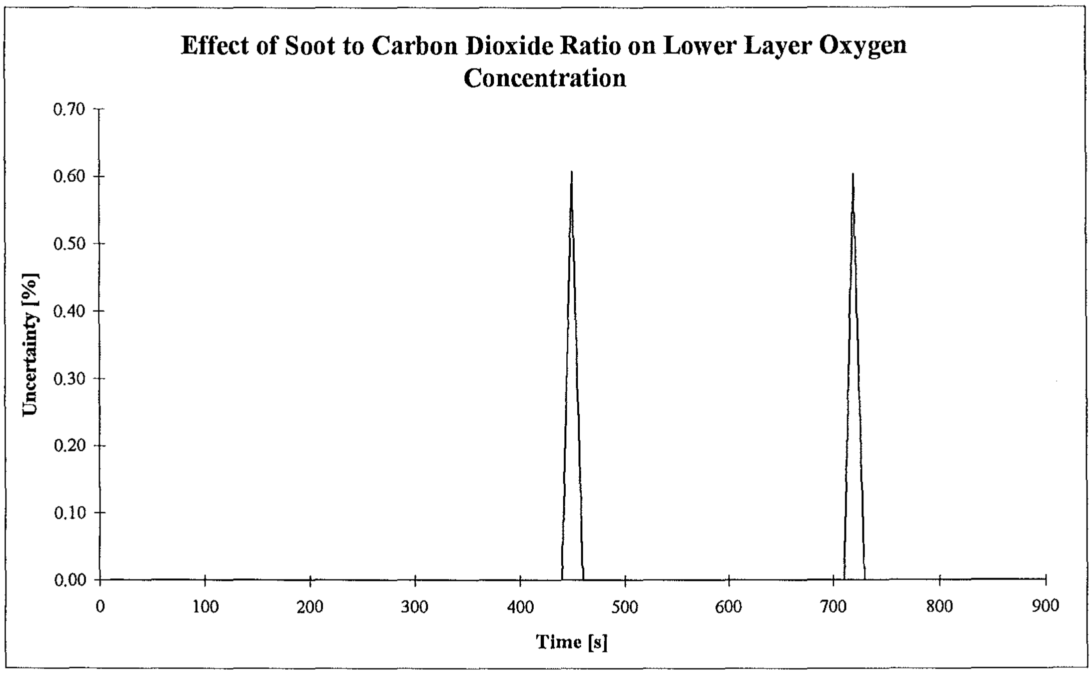
Effect of Soot to Carbon Dioxide Ratio on Vent Fire
Uncertainty [%]
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Soot to Carbon Dioxide Ratio on Radiation
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

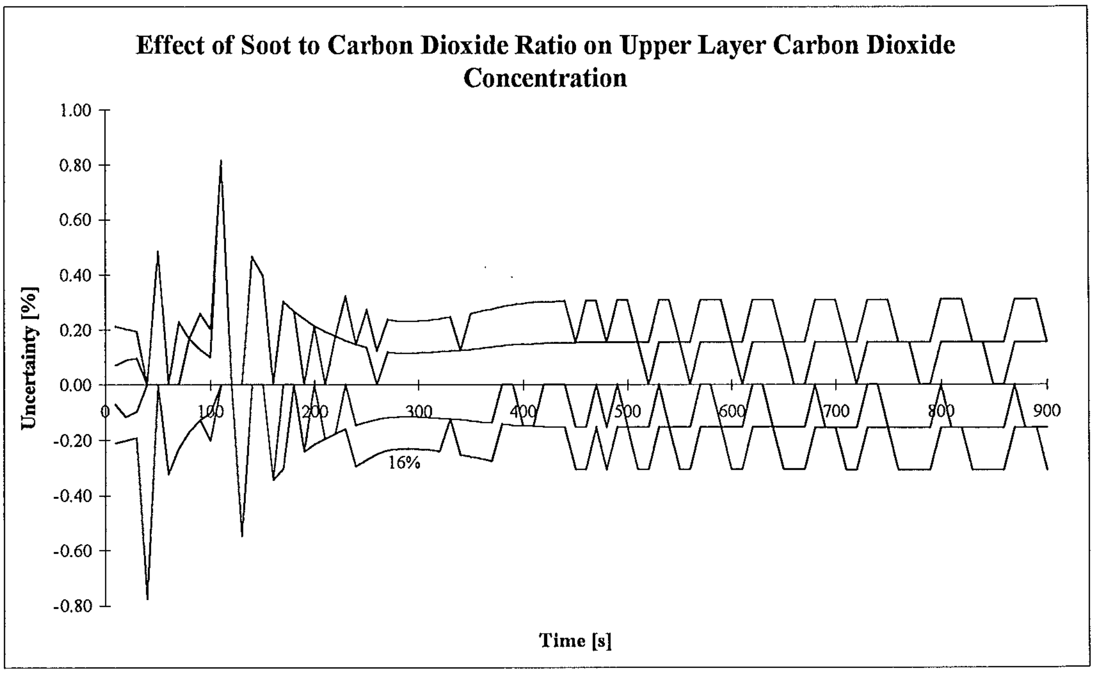

Effect of Soot to Carbon Dioxide Ratio on Convection
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



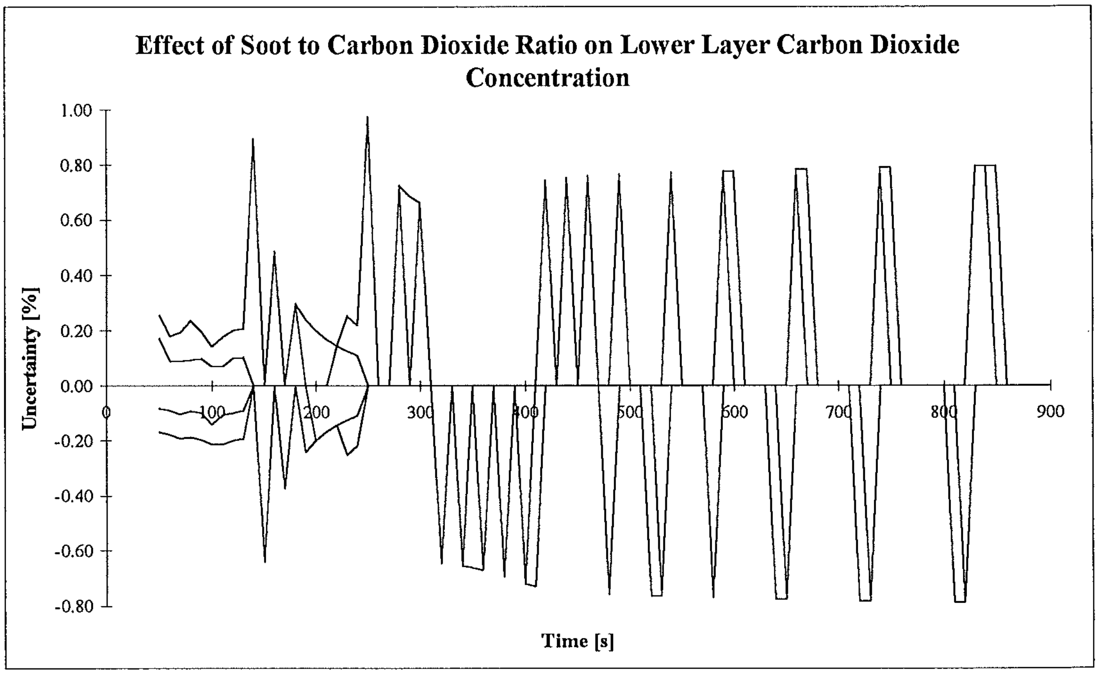
Effect of Soot to Carbon Dioxide Ratio on Upper Layer Oxygen Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



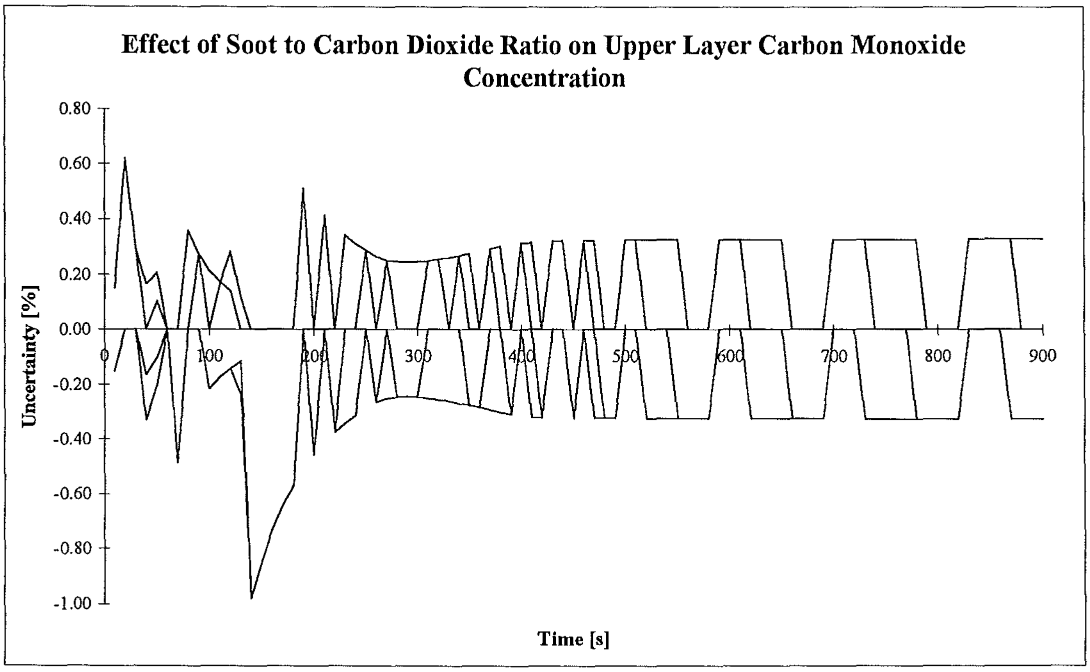
Effect of Soot to Carbon Dioxide Ratio on Lower Layer Oxygen Concentration
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]



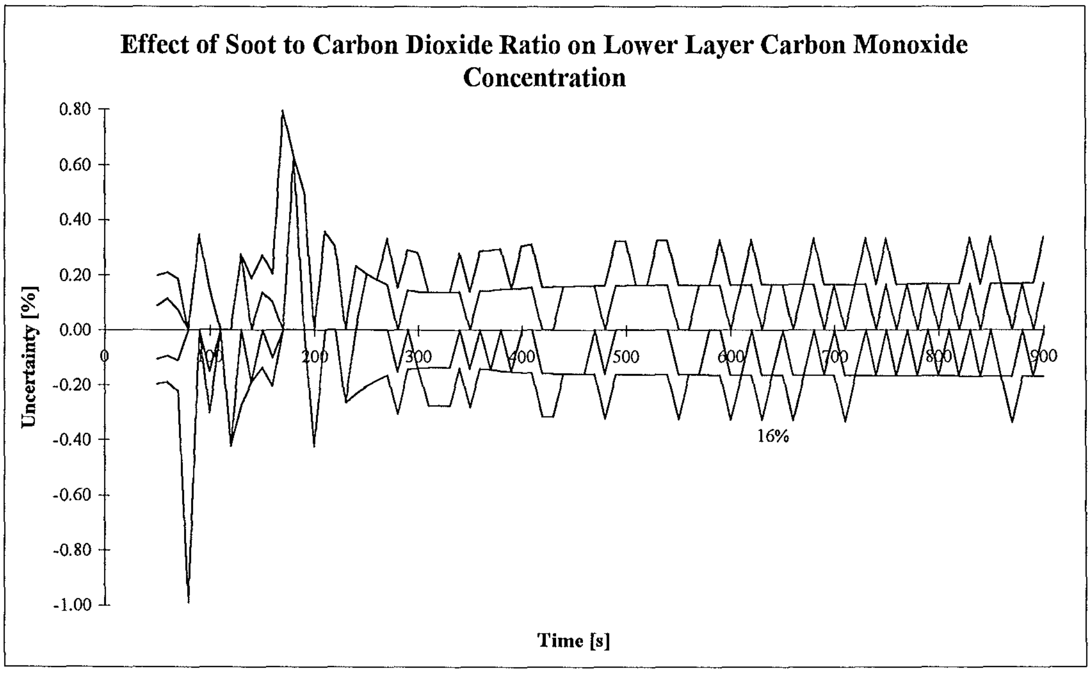
Effect of Soot to Carbon Dioxide Ratio on Upper Layer Carbon Dioxide Concentration
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
16%
Time [s]



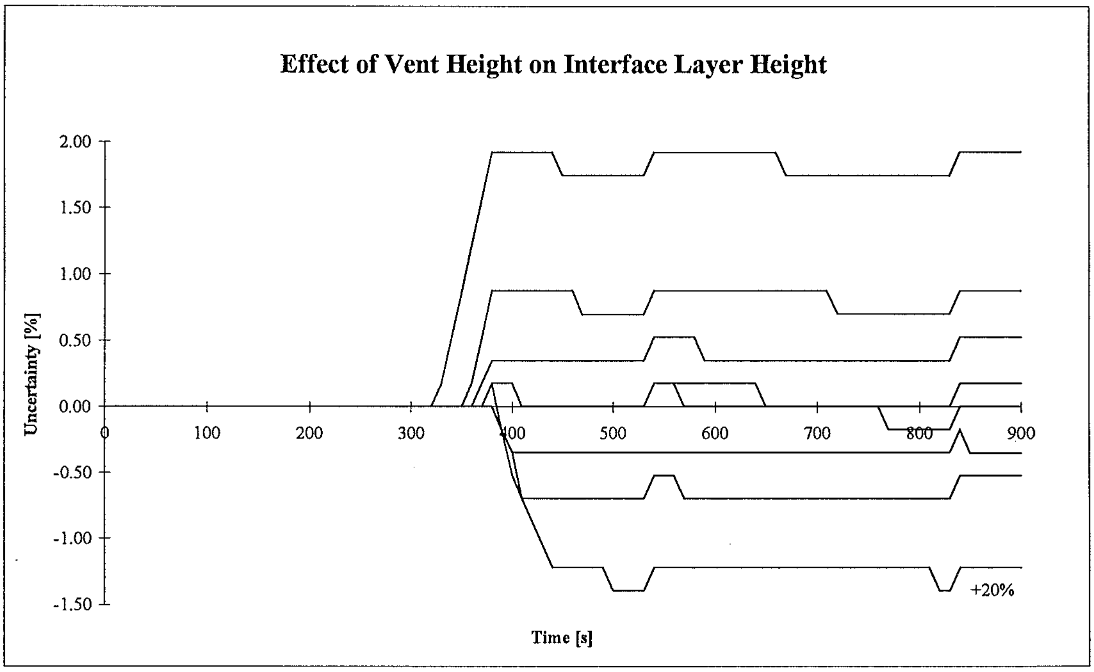
Effect of Soot to Carbon Dioxide Ratio on Lower Layer Carbon Dioxide Concentration
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

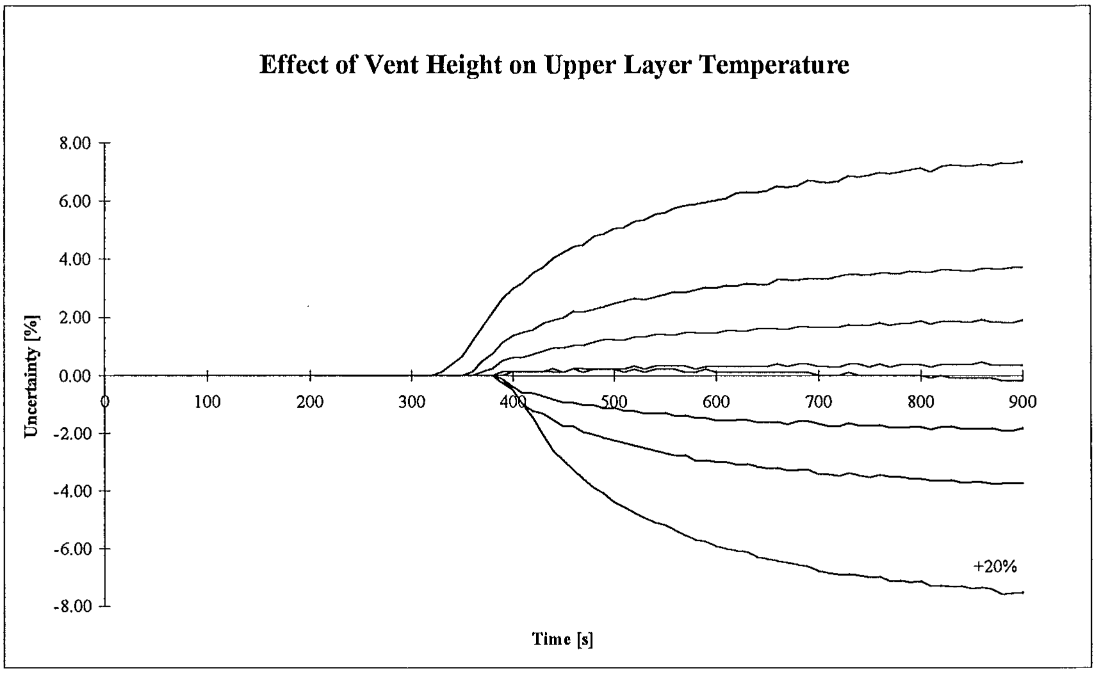


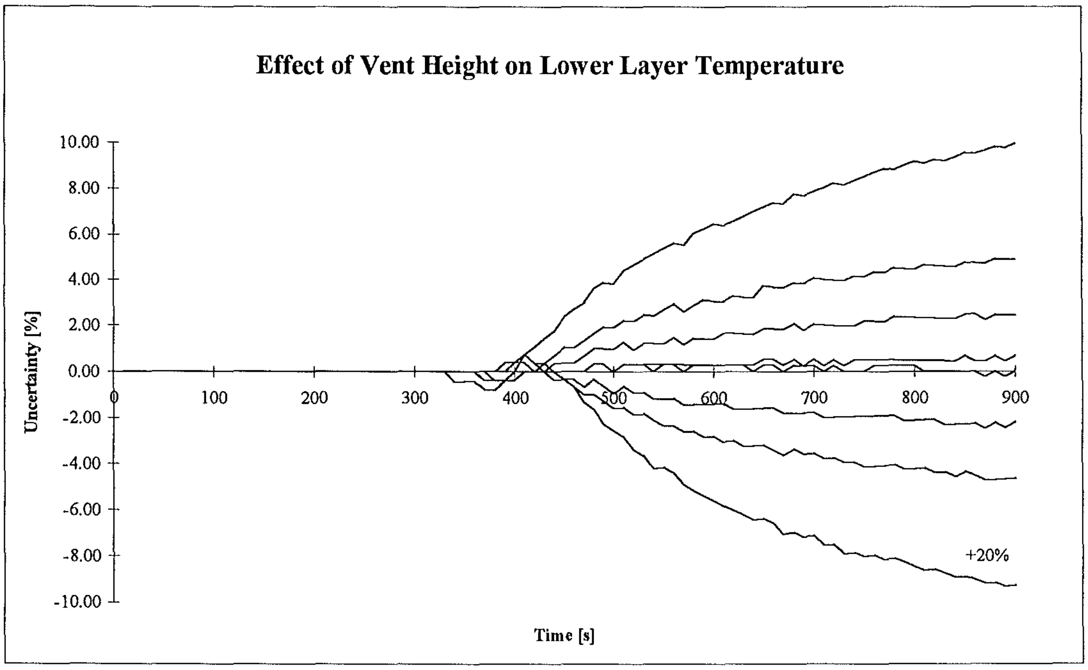
Effect of Soot to Carbon Dioxide Ratio on Upper Layer Carbon Monoxide Concentration
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

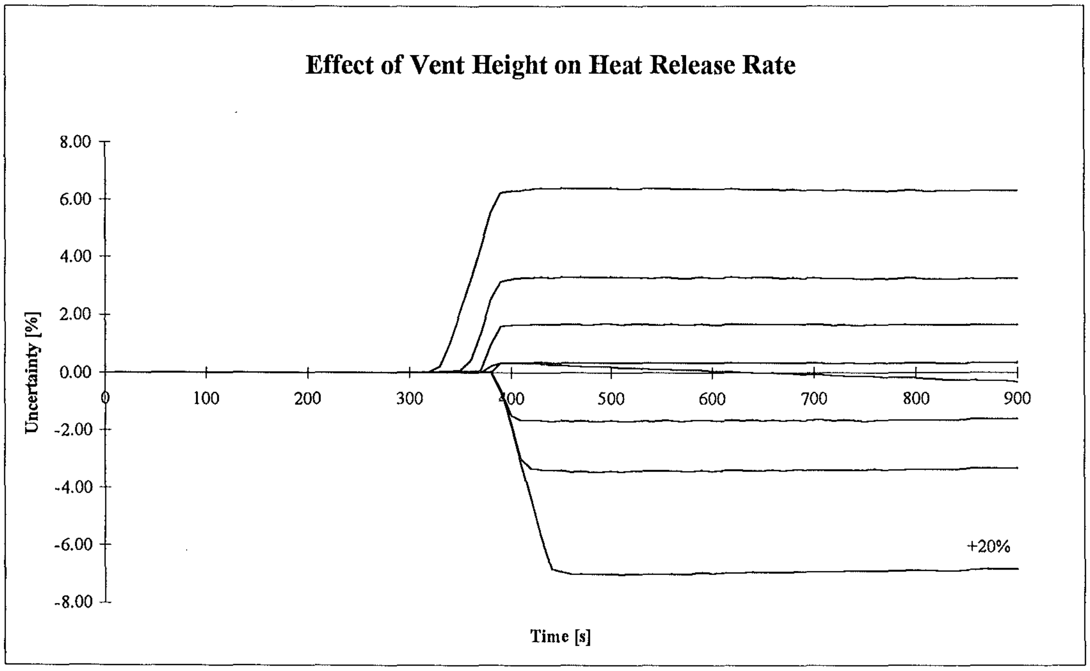


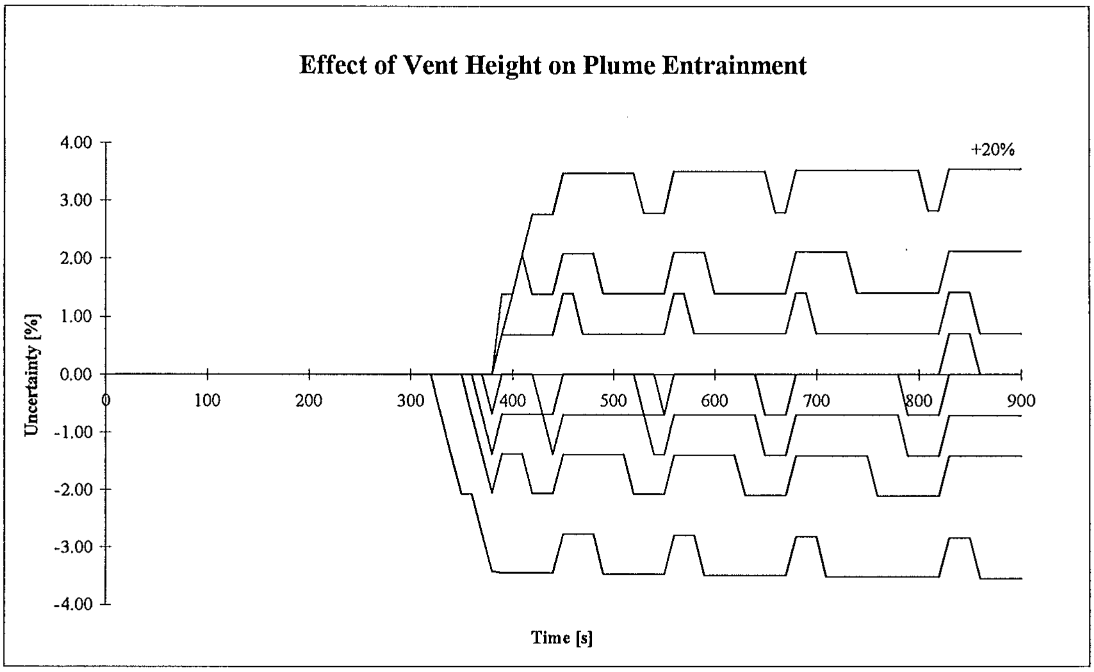
Effect of Soot to Carbon Dioxide Ratio on Lower Layer Carbon Monoxide Concentration
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
16%
Time [s]

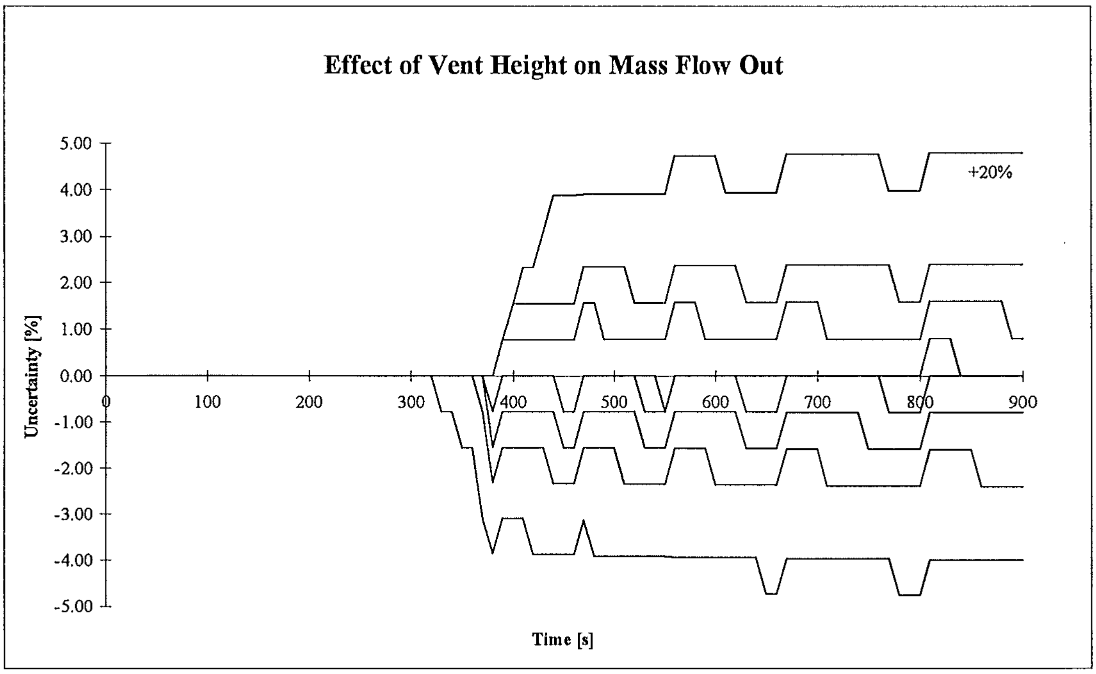

Effect of Vent Height on Interface Layer Height
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

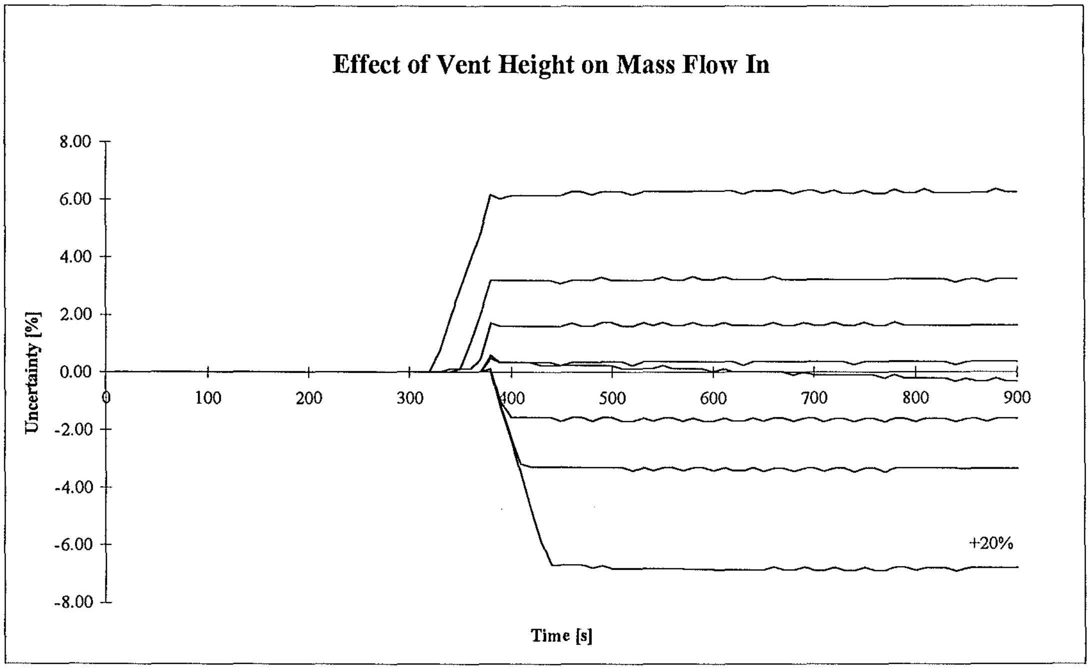

Effect of Vent Height on Upper Layer Temperature
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Height on Lower Layer Temperature
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

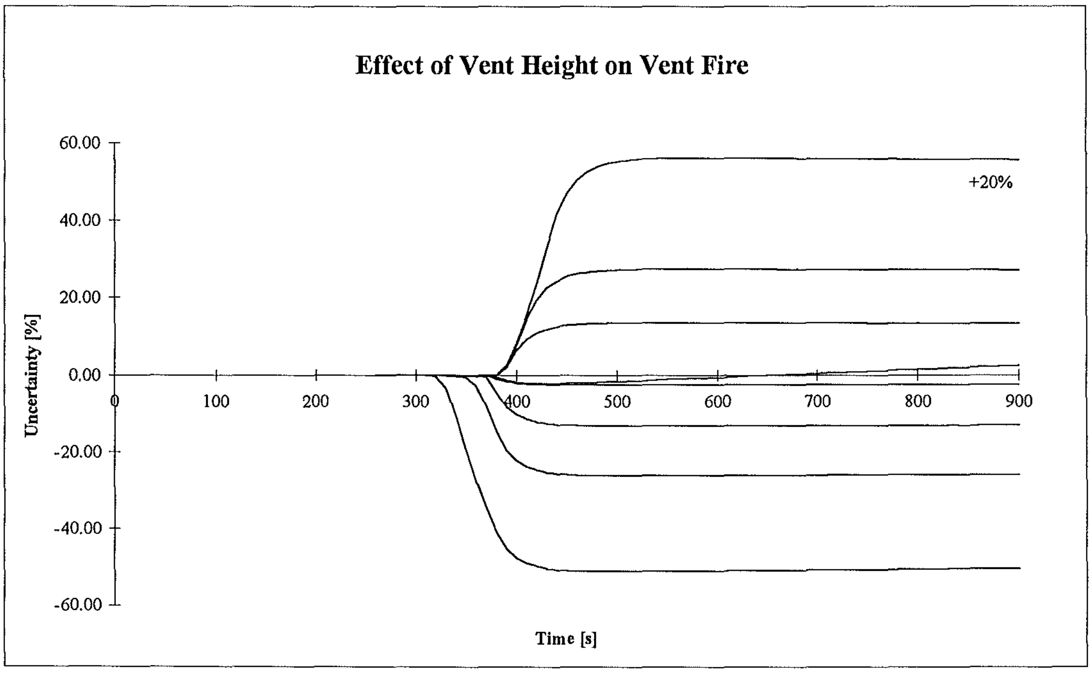

Effect of Vent Height on Heat Release Rate
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Height on Plume Entrainment
+20%
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

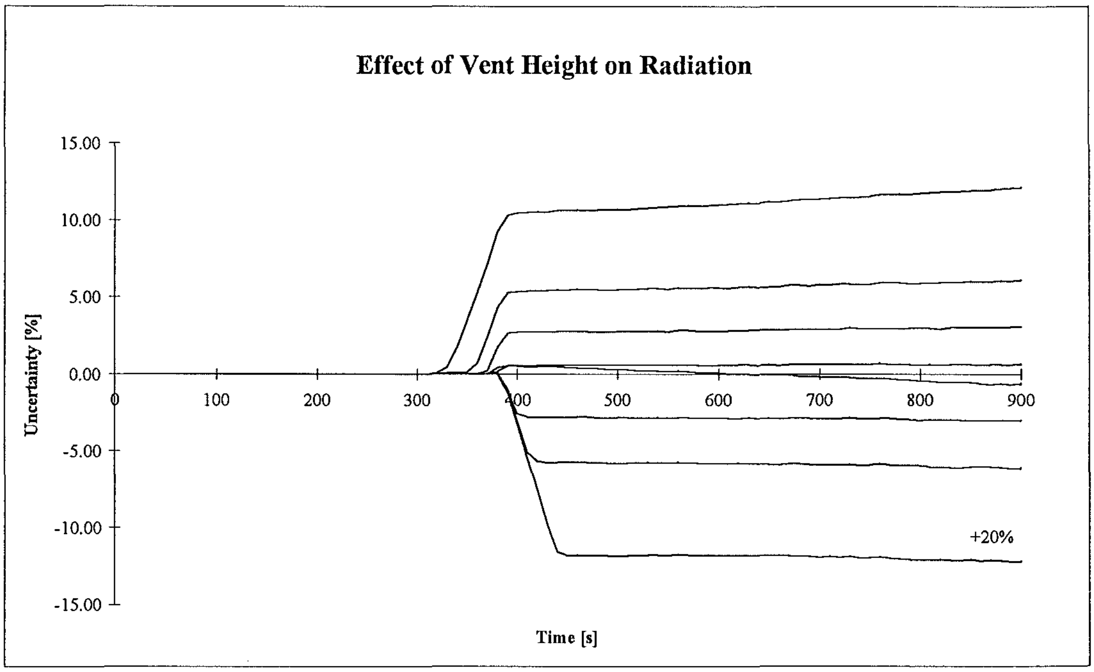

Effect of Vent Height on Mass Flow Out
+20%
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
Time [s]

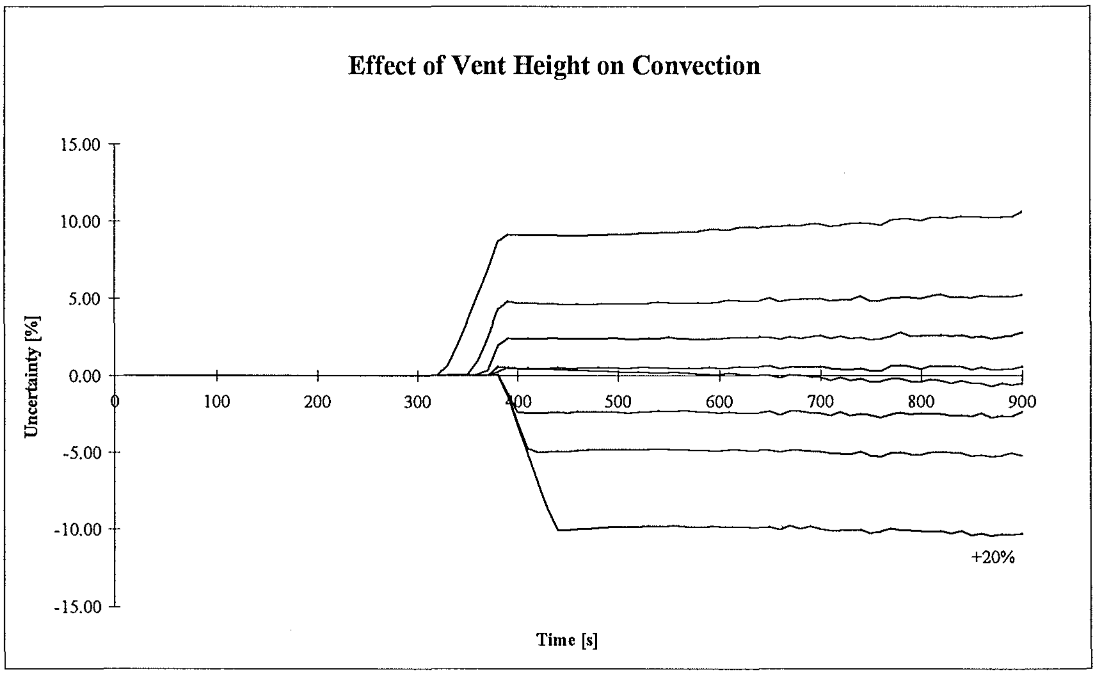


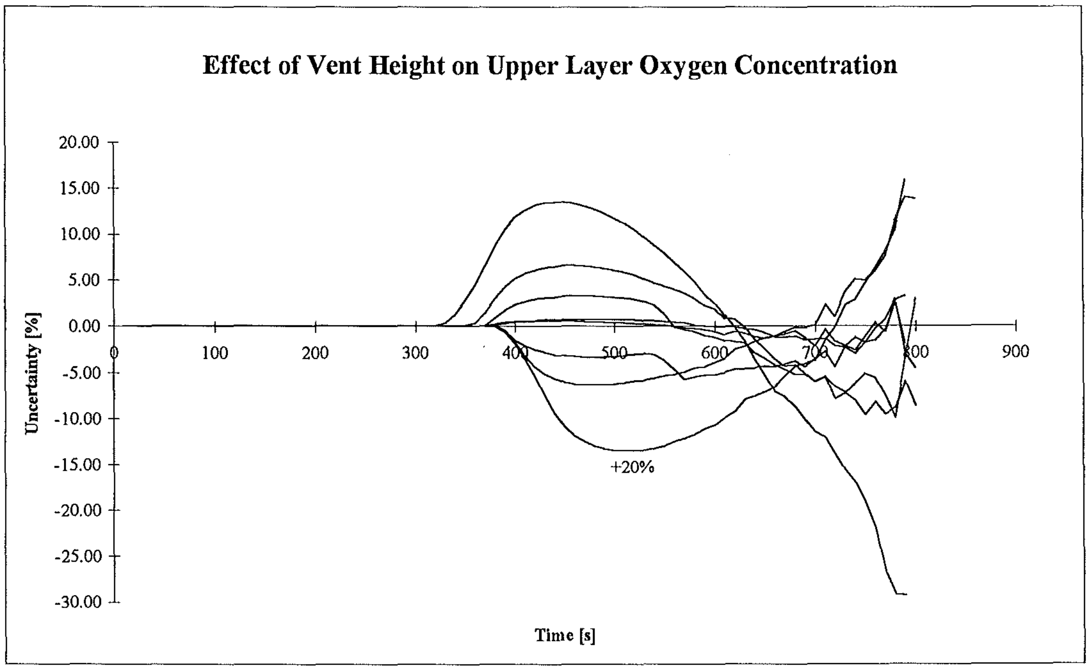
Effect of Vent Height on Mass Flow In
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

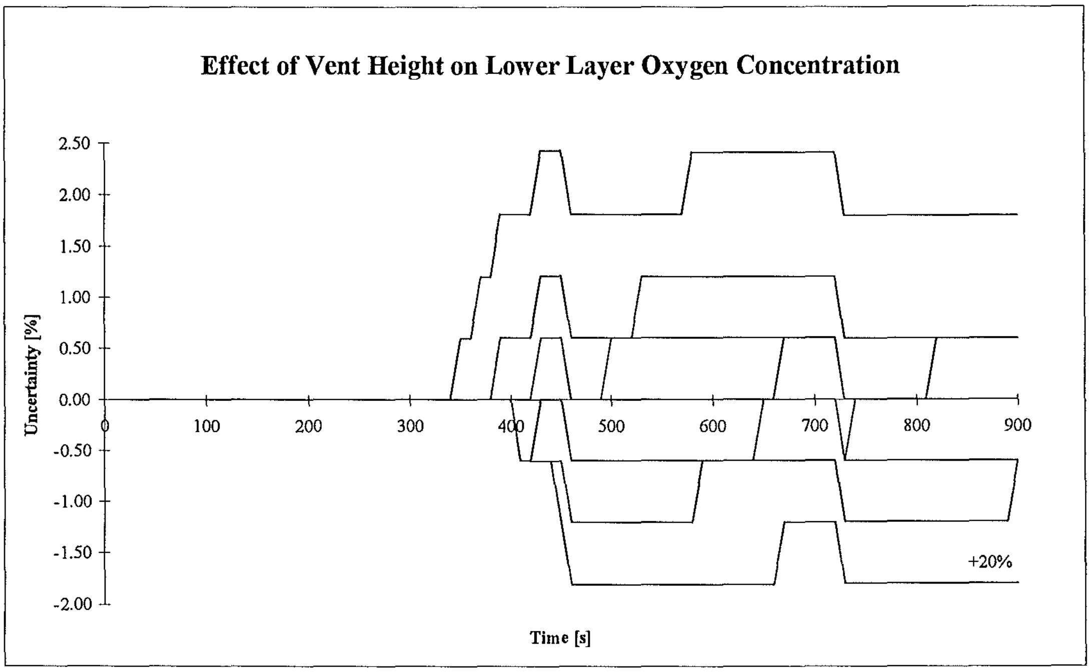


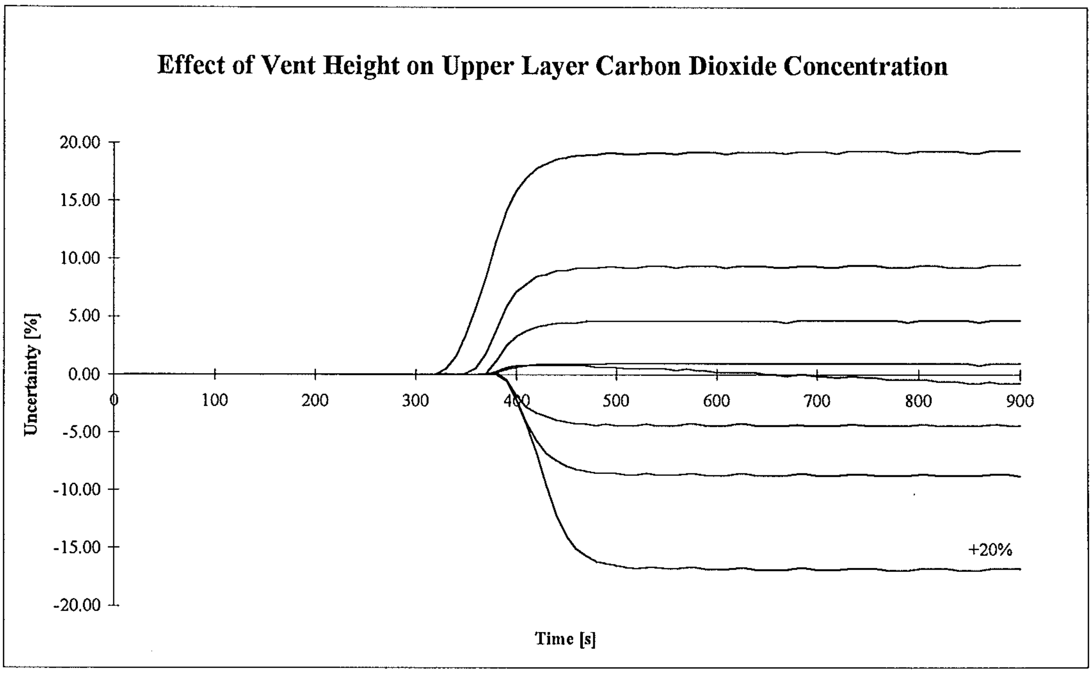
Effect of Vent Height on Vent Fire
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

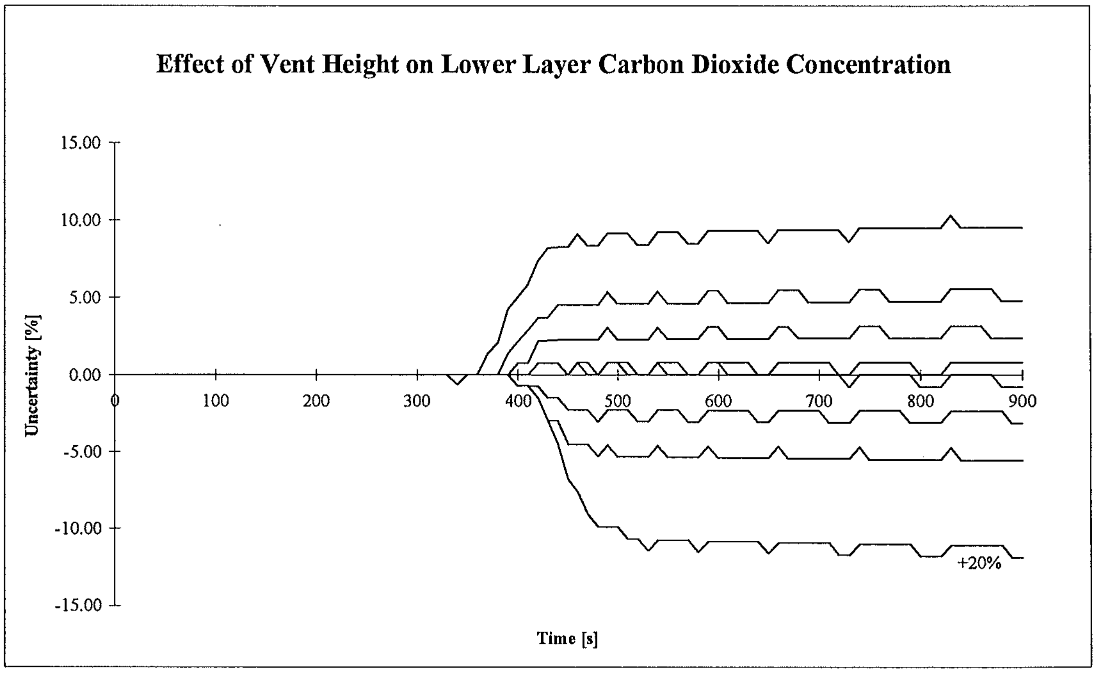

Effect of Vent Height on Radiation
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

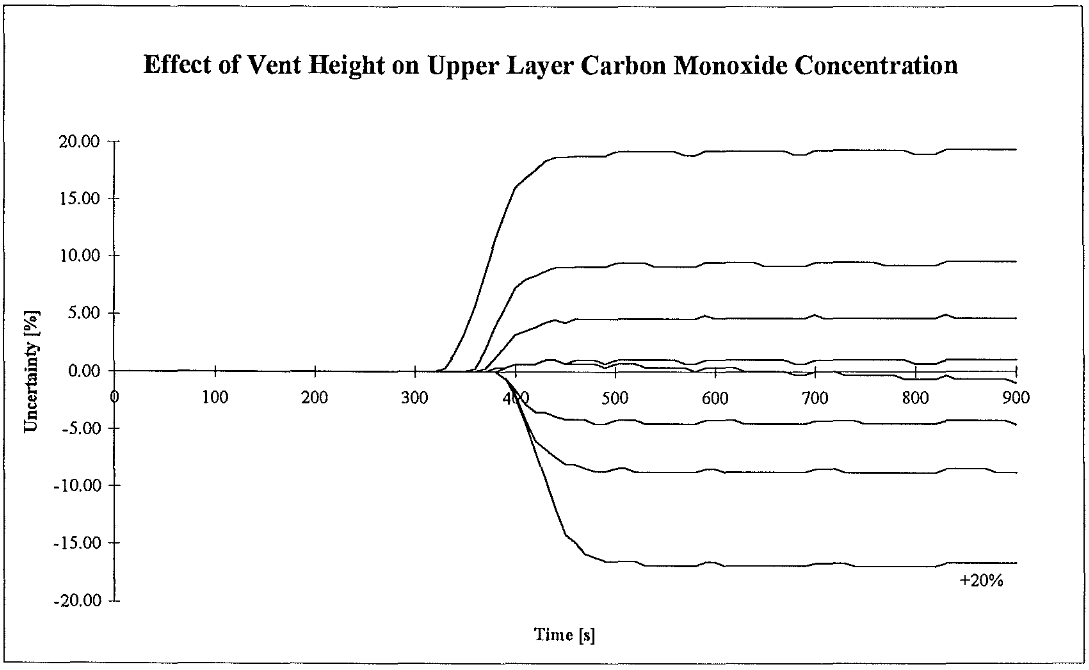

Effect of Vent Height on Convection
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Height on Upper Layer Oxygen Concentration
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

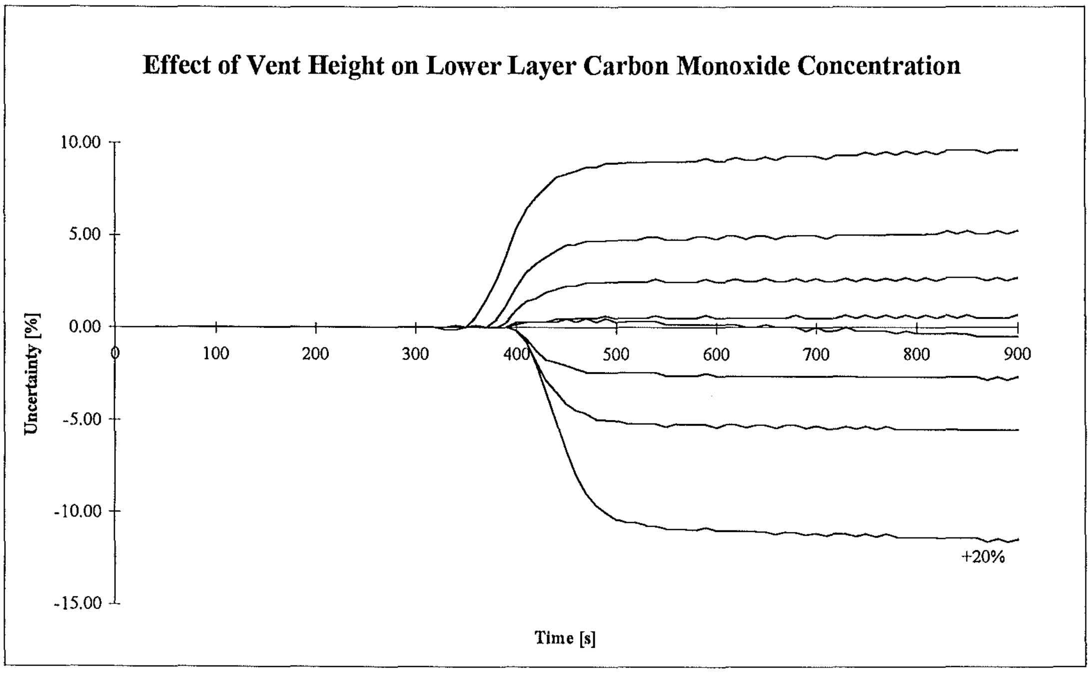

Effect of Vent Height on Lower Layer Oxygen Concentration
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Height on Upper Layer Carbon Dioxide Concentration
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

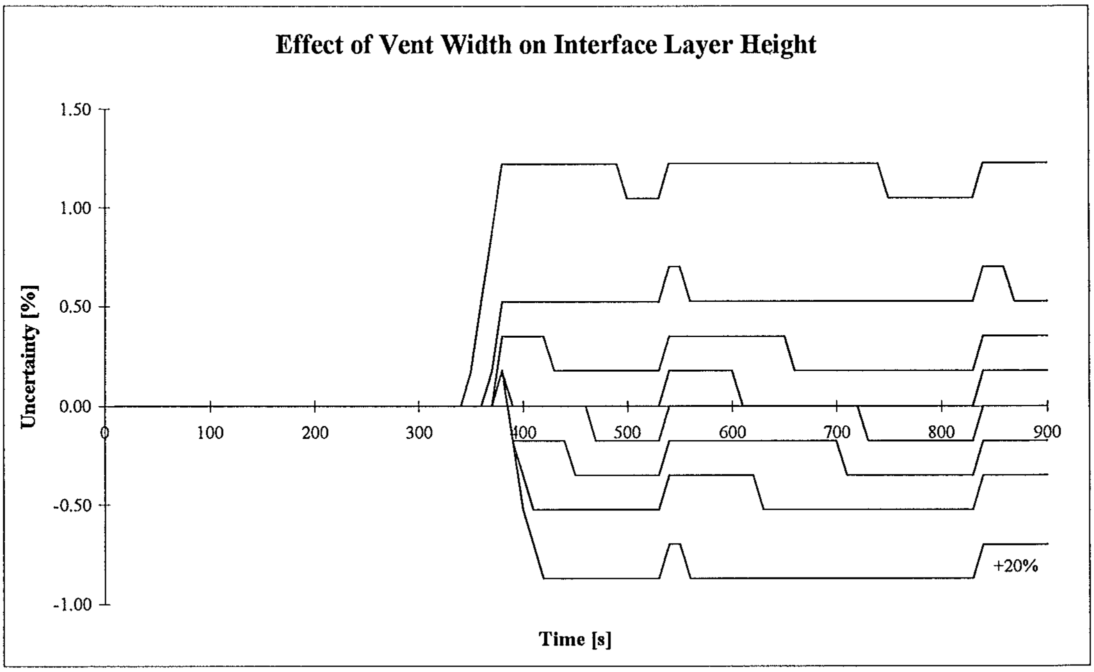

Effect of Vent Height on Lower Layer Carbon Dioxide Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

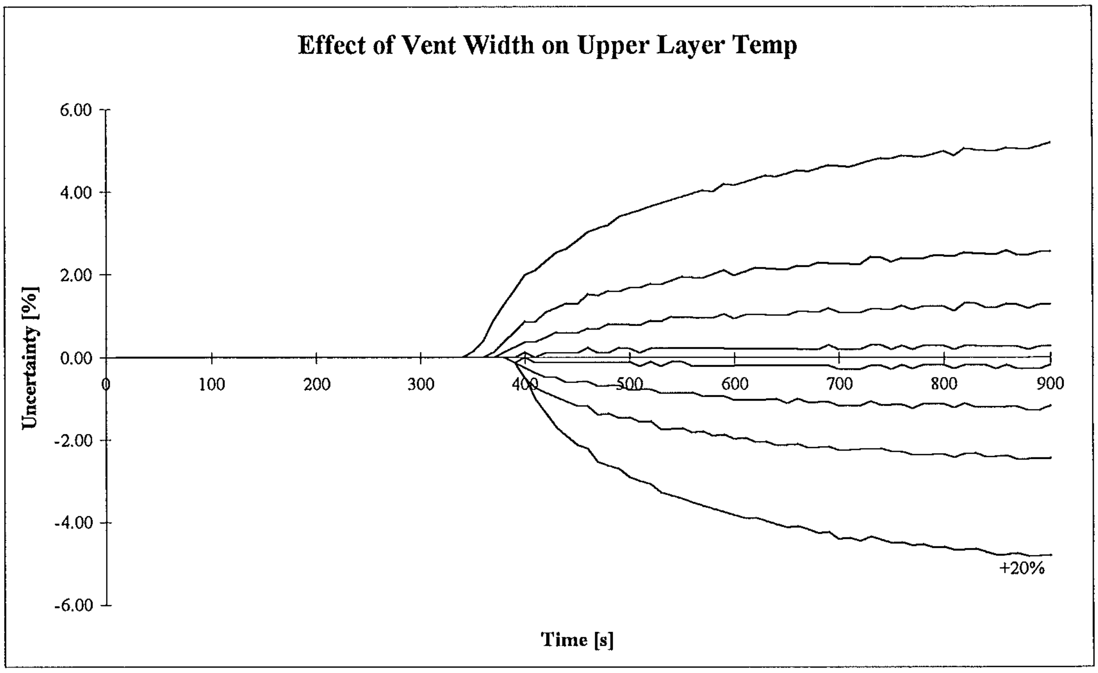


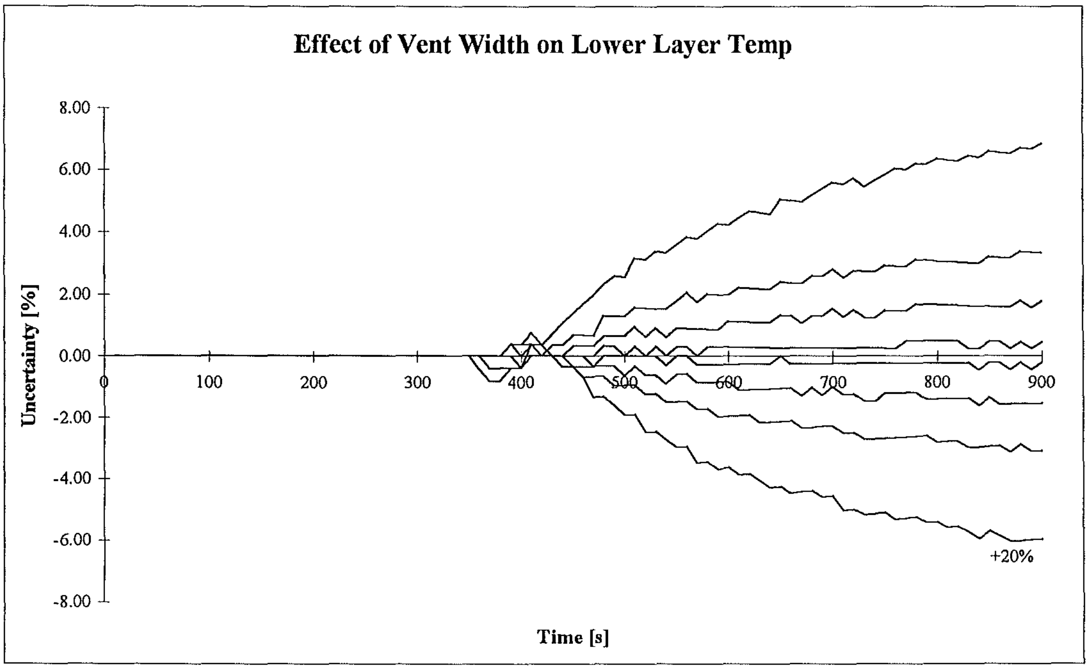
Effect of Vent Height on Upper Layer Carbon Monoxide Concentration
Uncertainty [%]
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

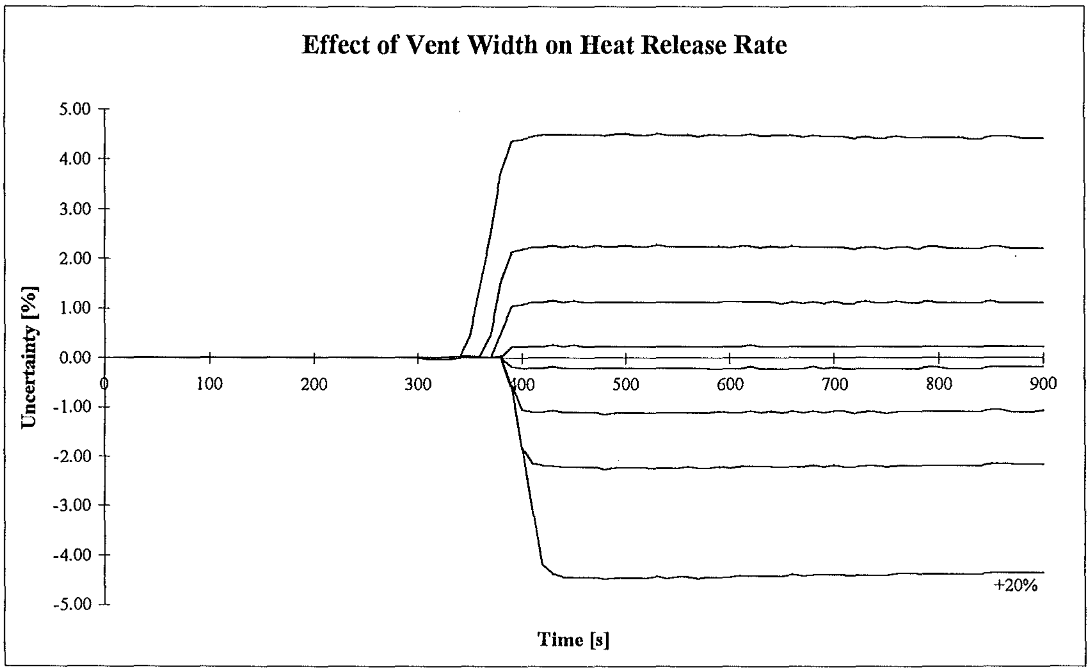


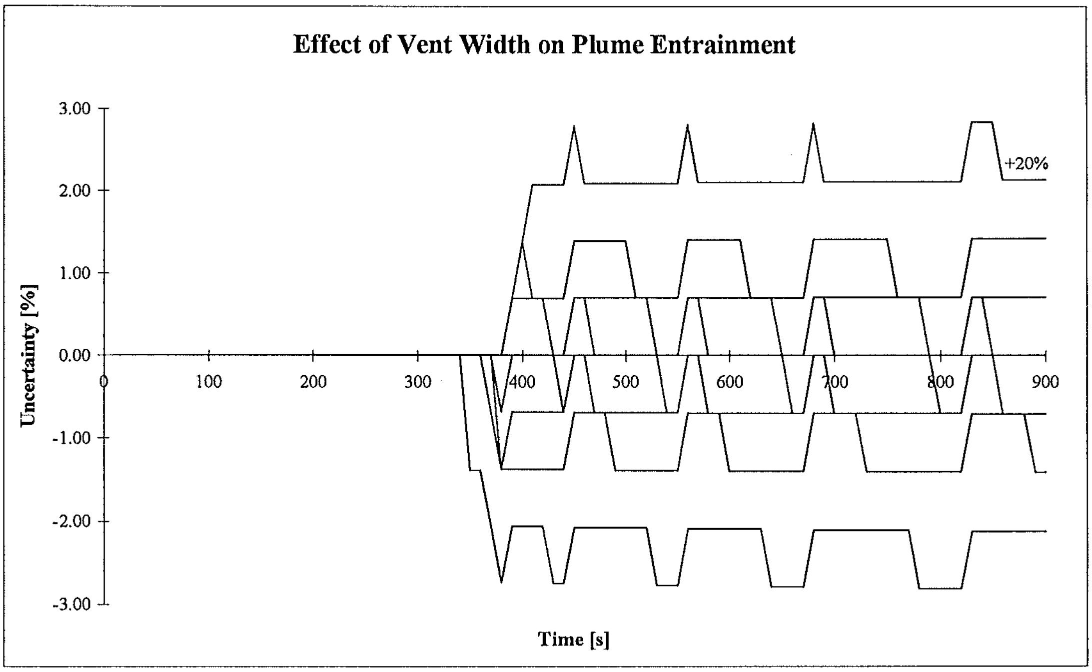
Effect of Vent Height on Lower Layer Carbon Monoxide Concentration
Uncertainty [%]
10.00
5.00
0.00
-5.00
-10.00
-15.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

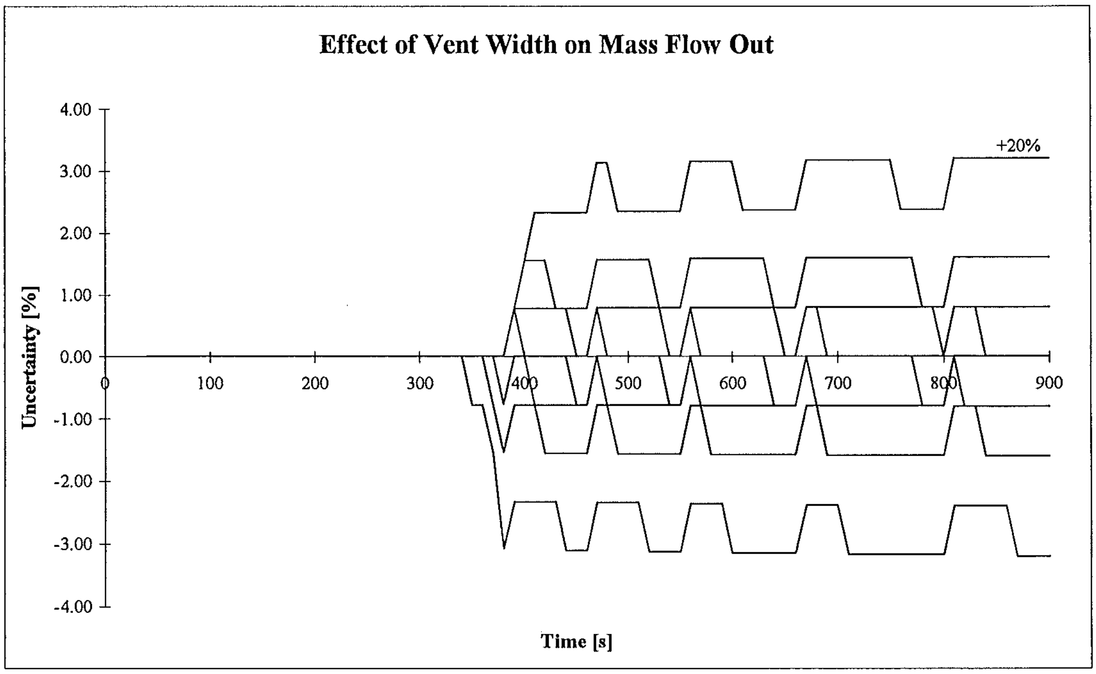

Effect of Vent Width on Interface Layer Height
1.50
1.00
0.50
0.00
-0.50
-1.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

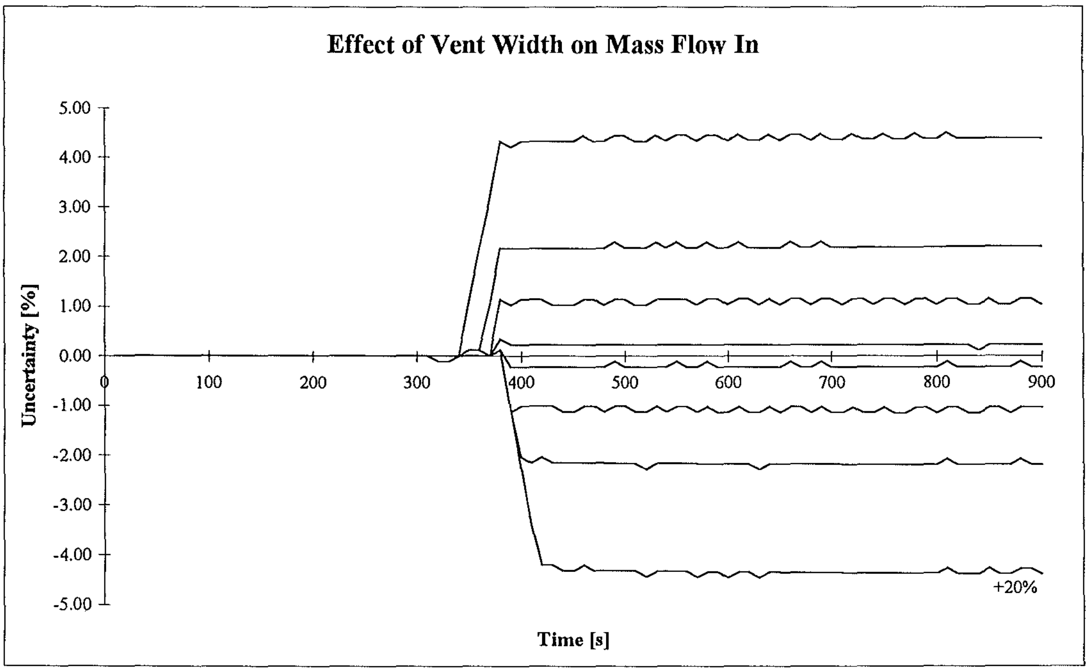

Effect of Vent Width on Upper Layer Temp
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

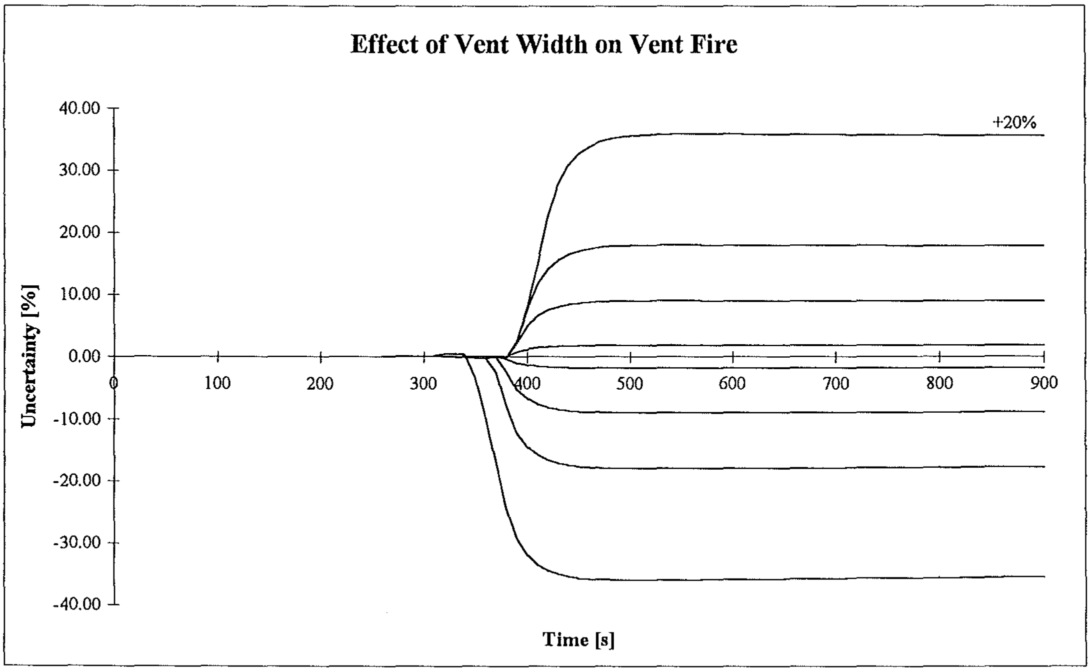

Effect of Vent Width on Lower Layer Temp
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

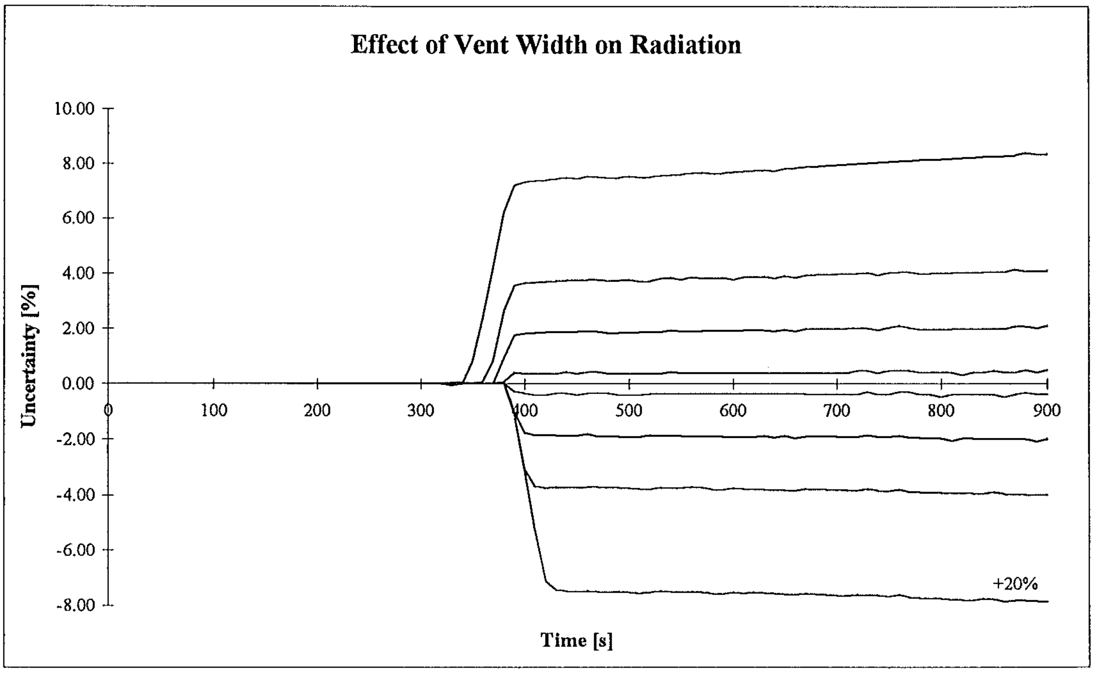

Effect of Vent Width on Heat Release Rate
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Width on Plume Entrainment
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

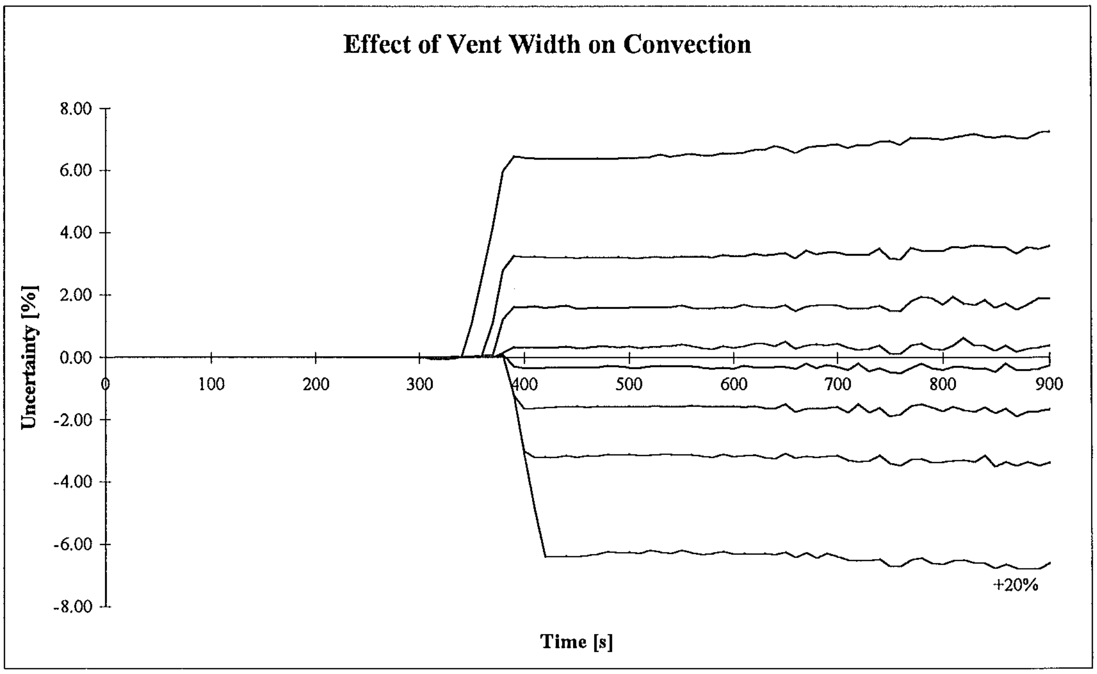

Effect of Vent Width on Mass Flow Out
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Width on Mass Flow In
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

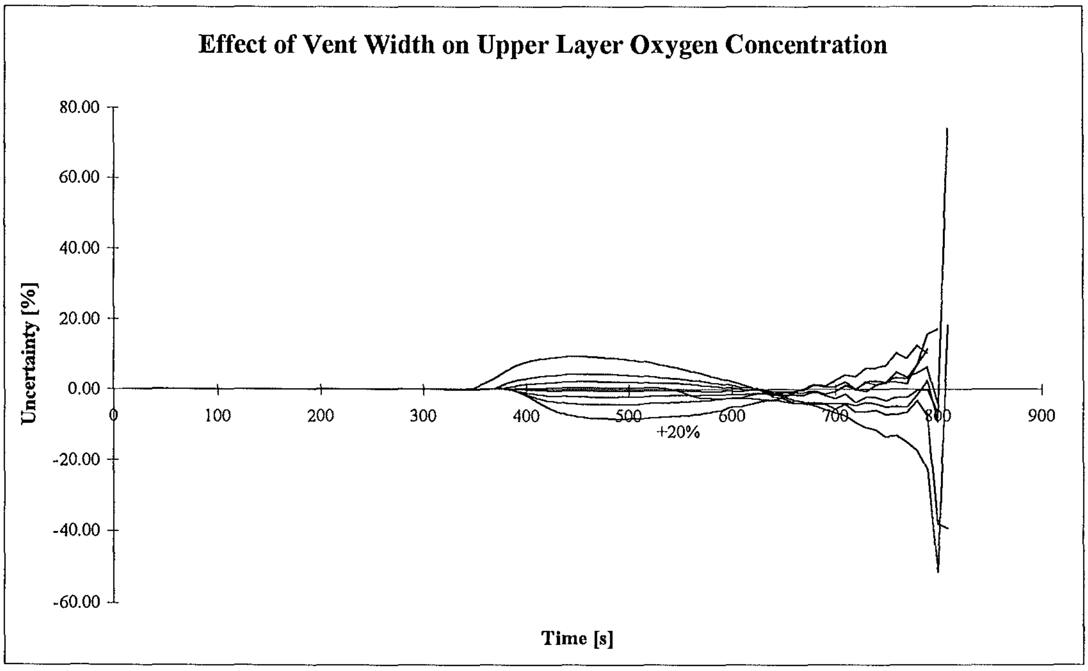

Effect of Vent Width on Vent Fire
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

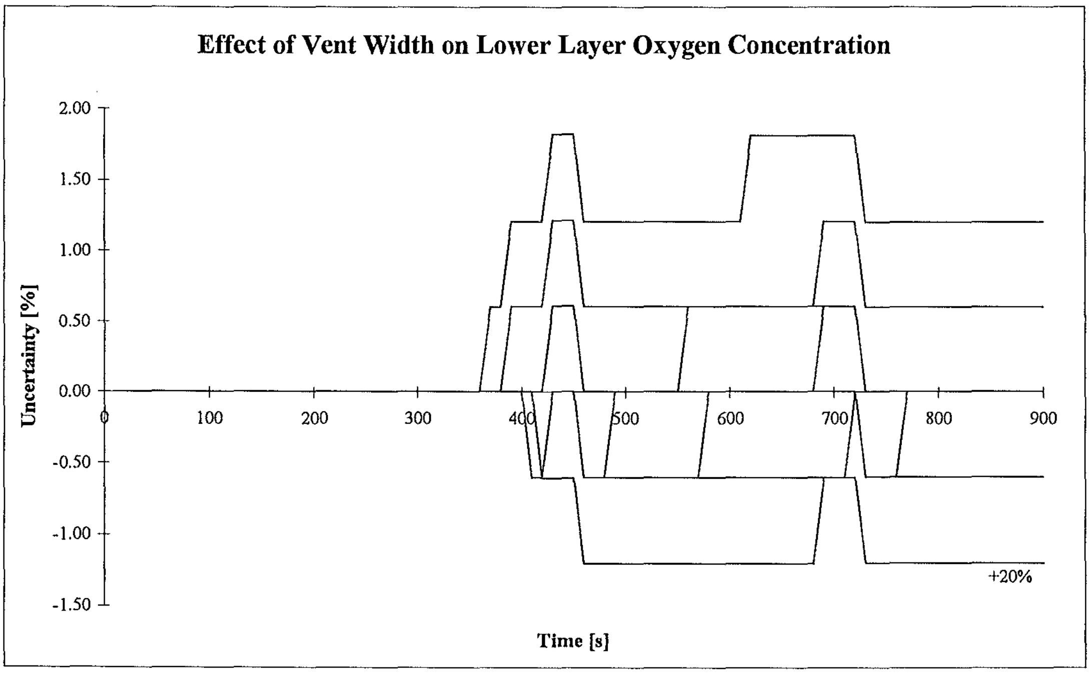


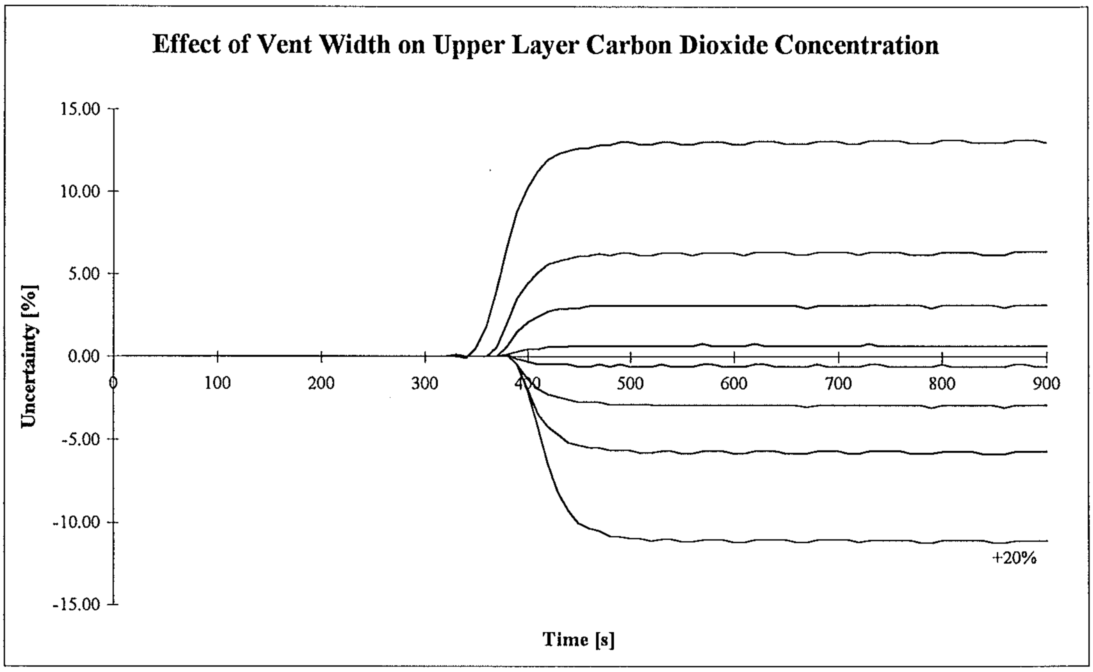
Effect of Vent Width on Radiation
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

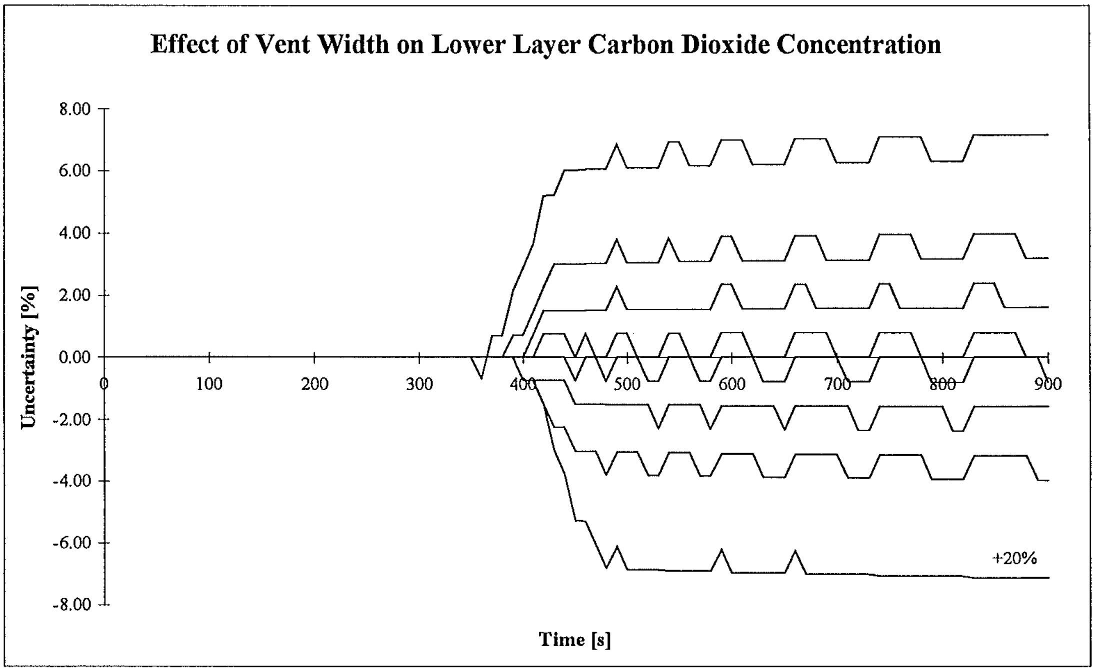


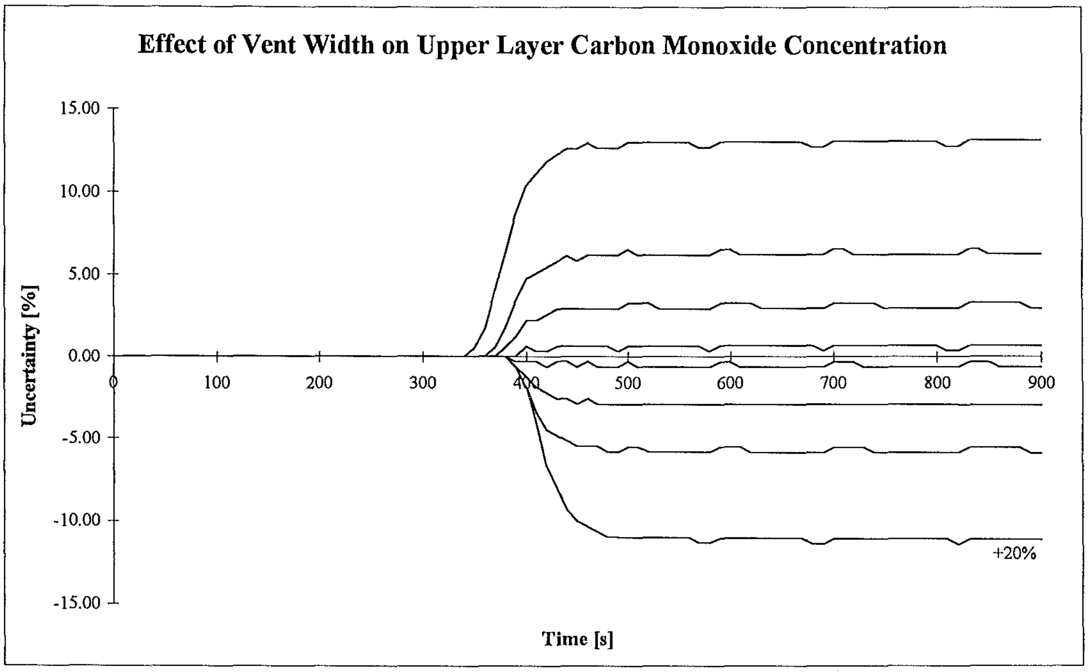
Effect of Vent Width on Convection
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

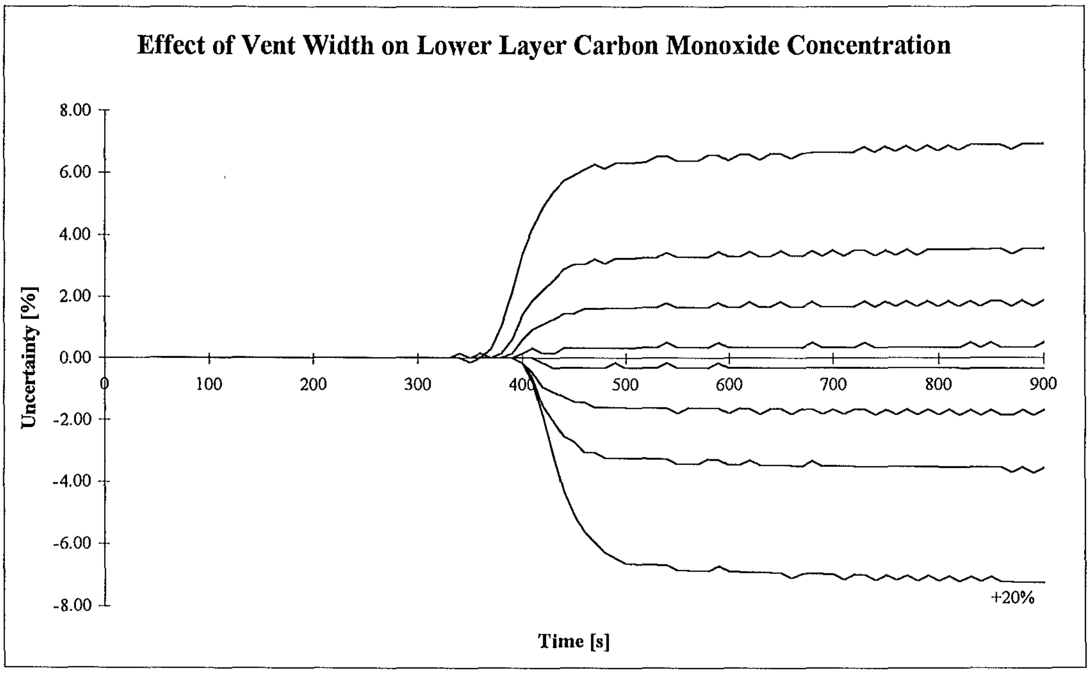

Effect of Vent Width on Upper Layer Oxygen Concentration
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

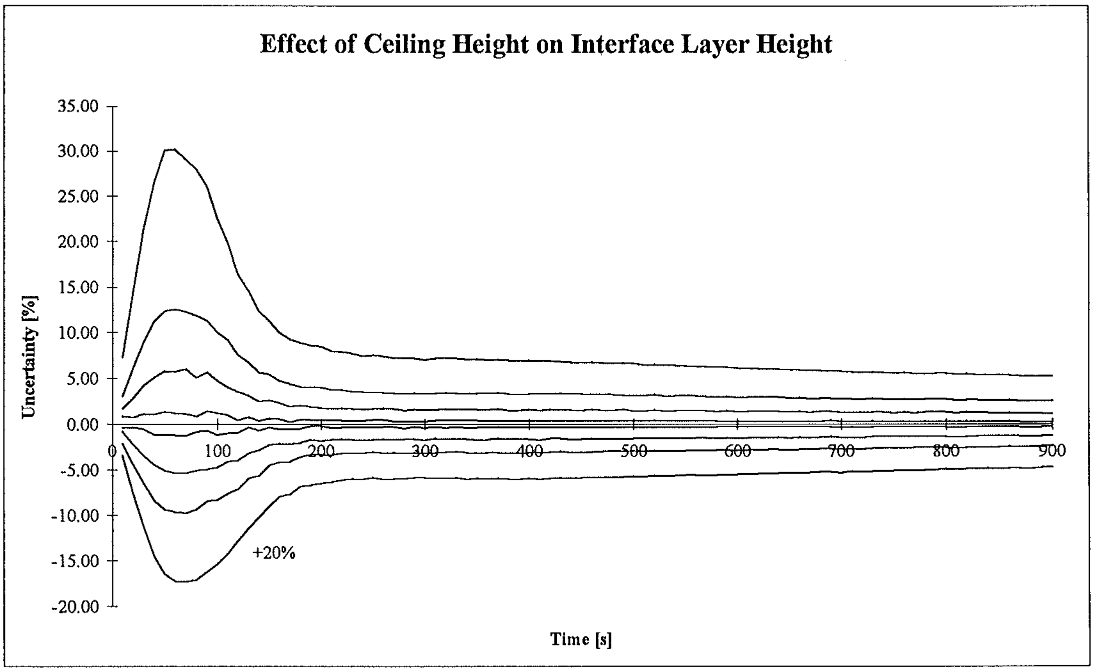

Effect of Vent Width on Lower Layer Oxygen Concentration
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Width on Upper Layer Carbon Dioxide Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

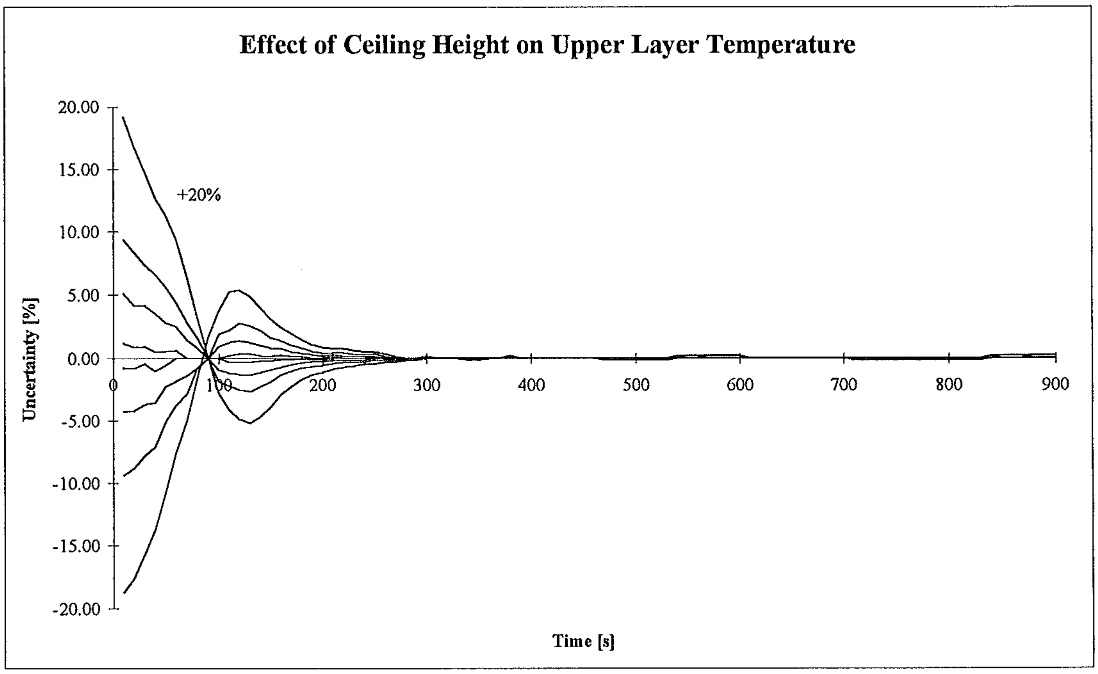

Effect of Vent Width on Lower Layer Carbon Dioxide Concentration
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Vent Width on Upper Layer Carbon Monoxide Concentration
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

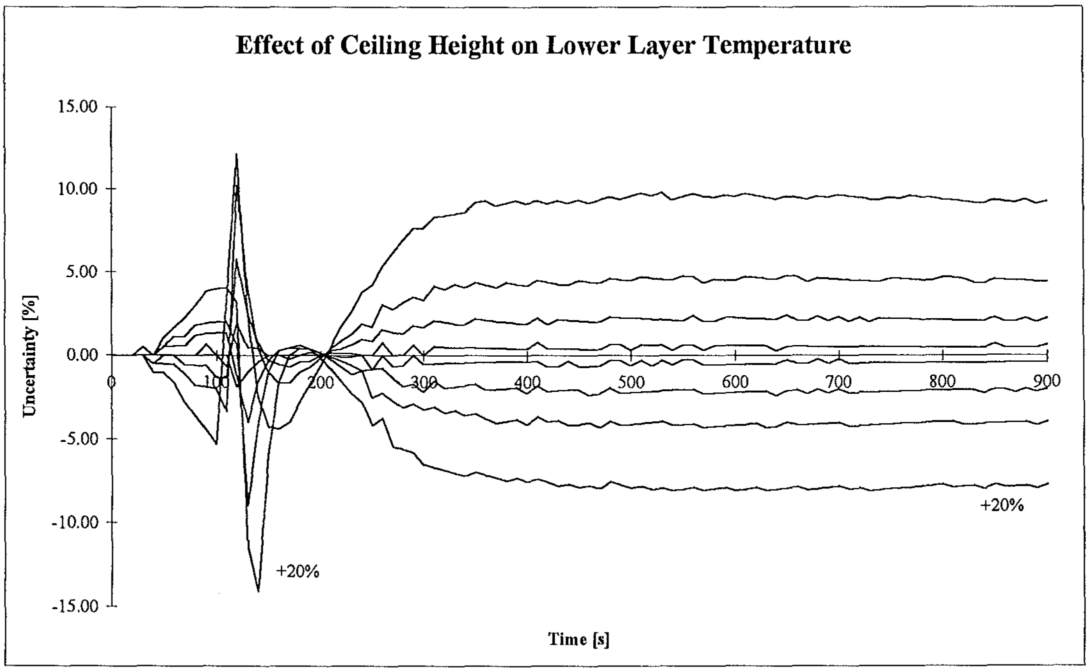

Effect of Vent Width on Lower Layer Carbon Monoxide Concentration
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



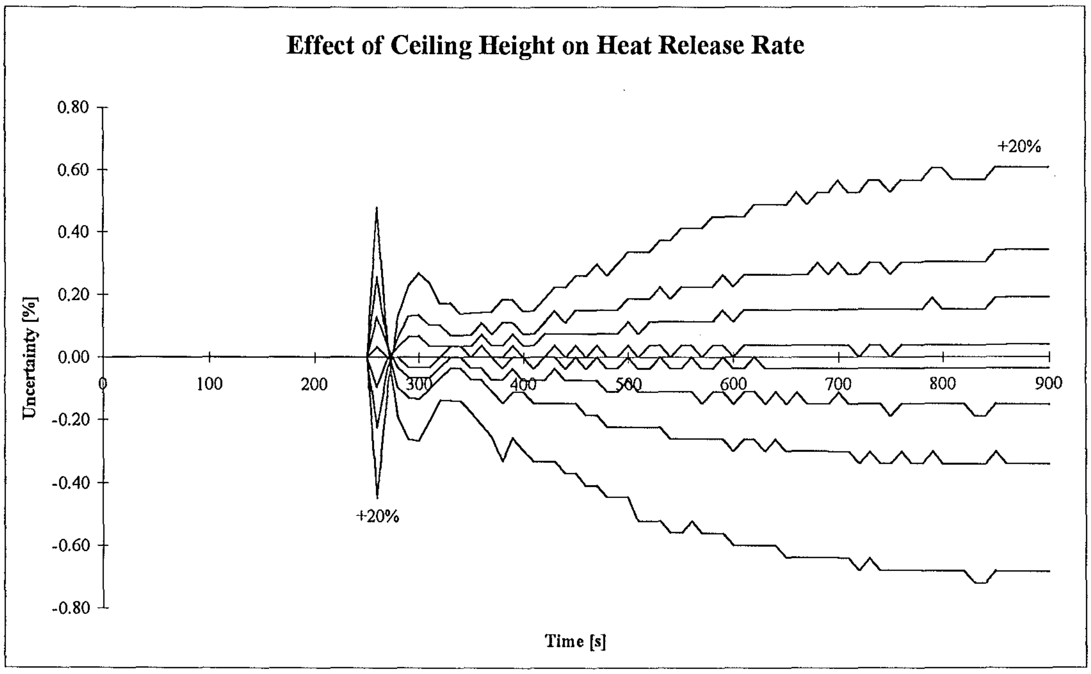
Effect of Ceiling Height on Interface Layer Height
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



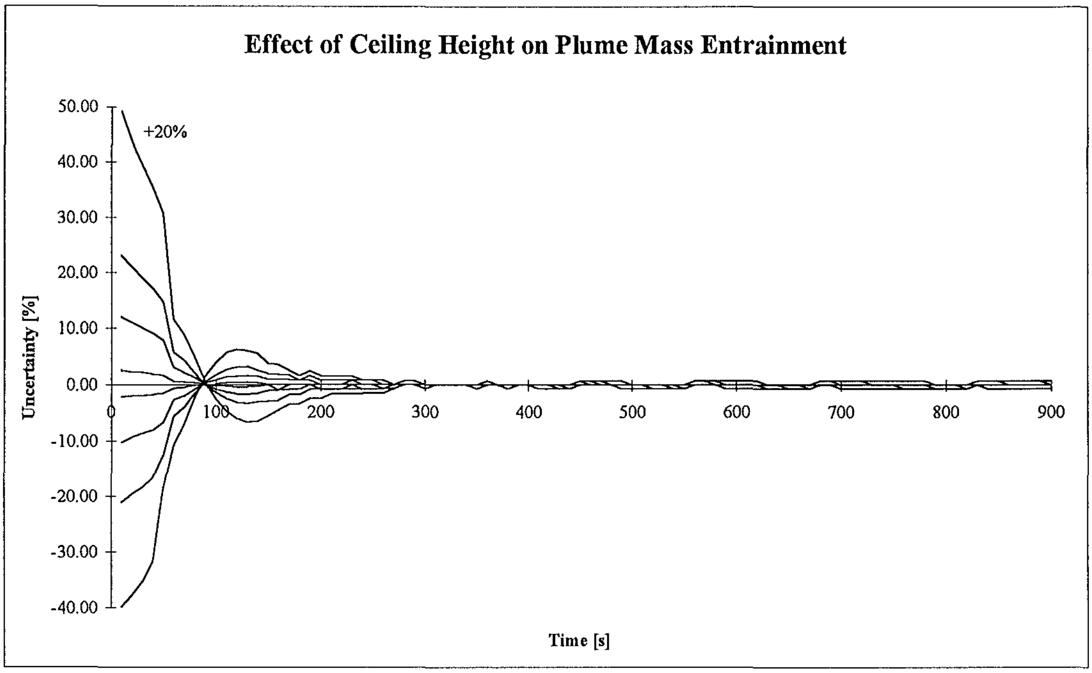
Effect of Ceiling Height on Upper Layer Temperature
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]



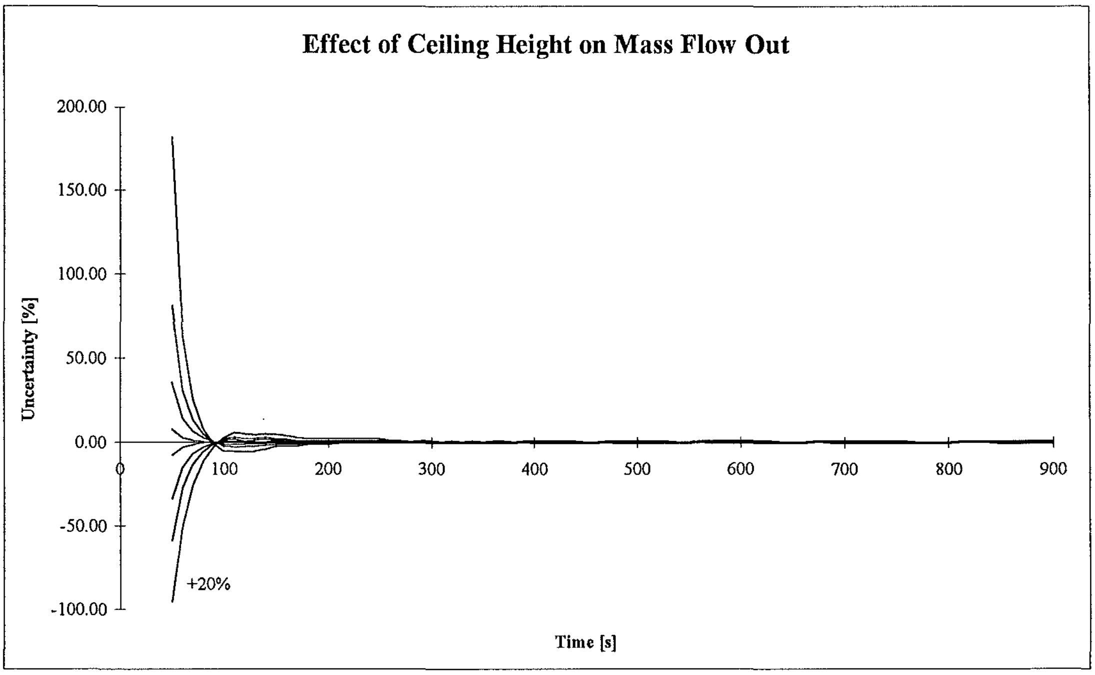
Effect of Ceiling Height on Lower Layer Temperature
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+20%
Time [s]



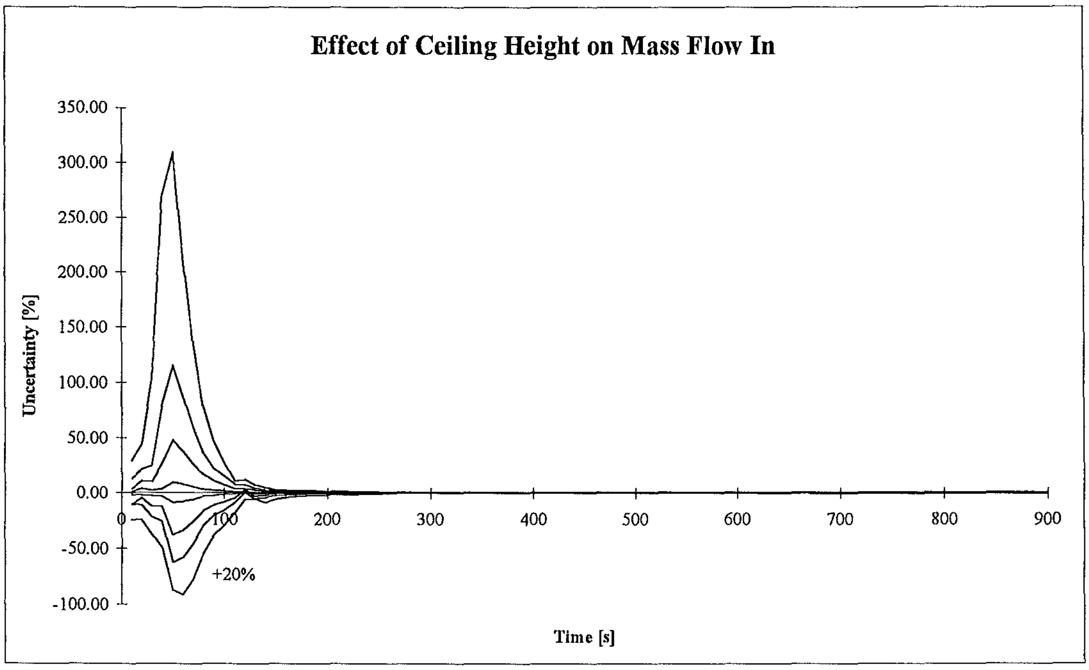
Effect of Ceiling Height on Heat Release Rate
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
+20%
Time [s]

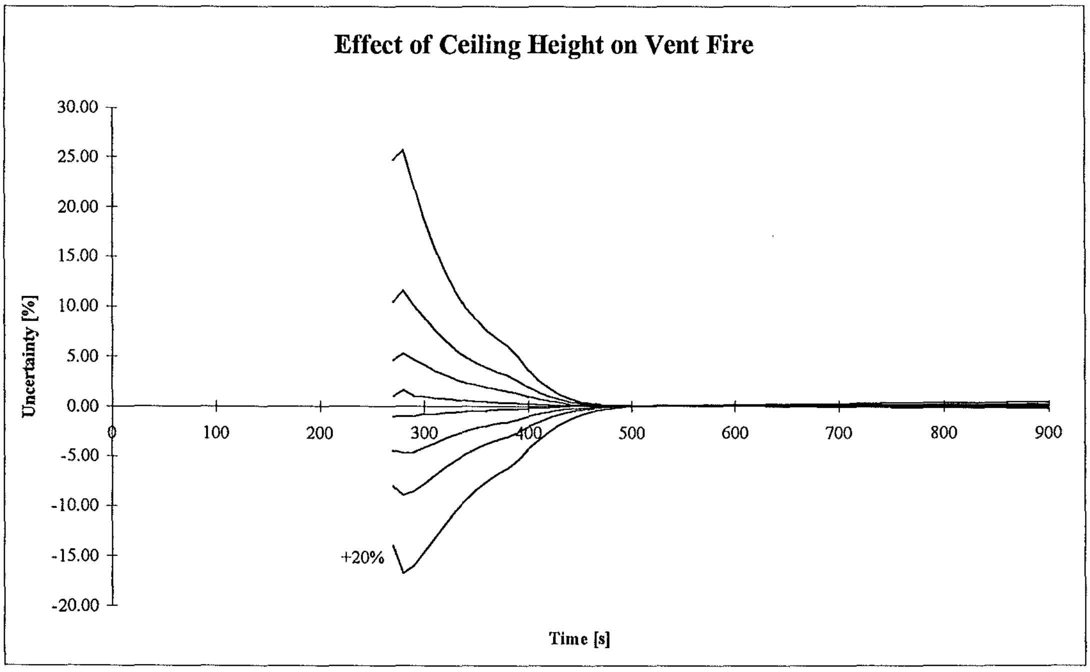


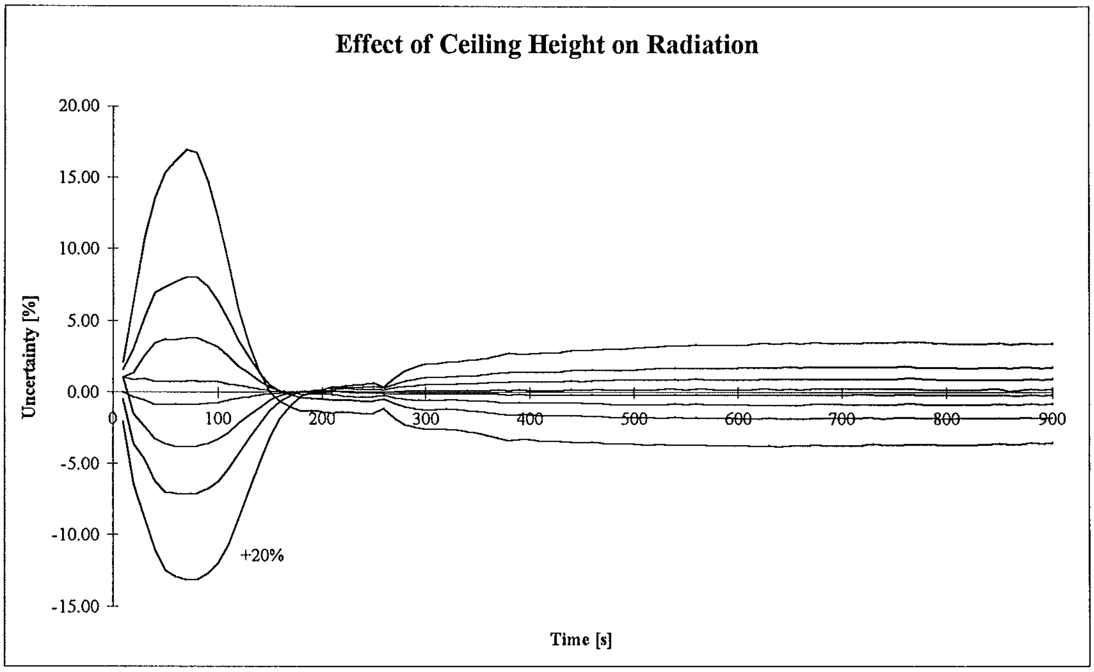
Effect of Ceiling Height on Plume Mass Entrainment
+20%
Uncertainty [%]
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
0
100
200
300
400
500
600
700
800
900
Time [s]



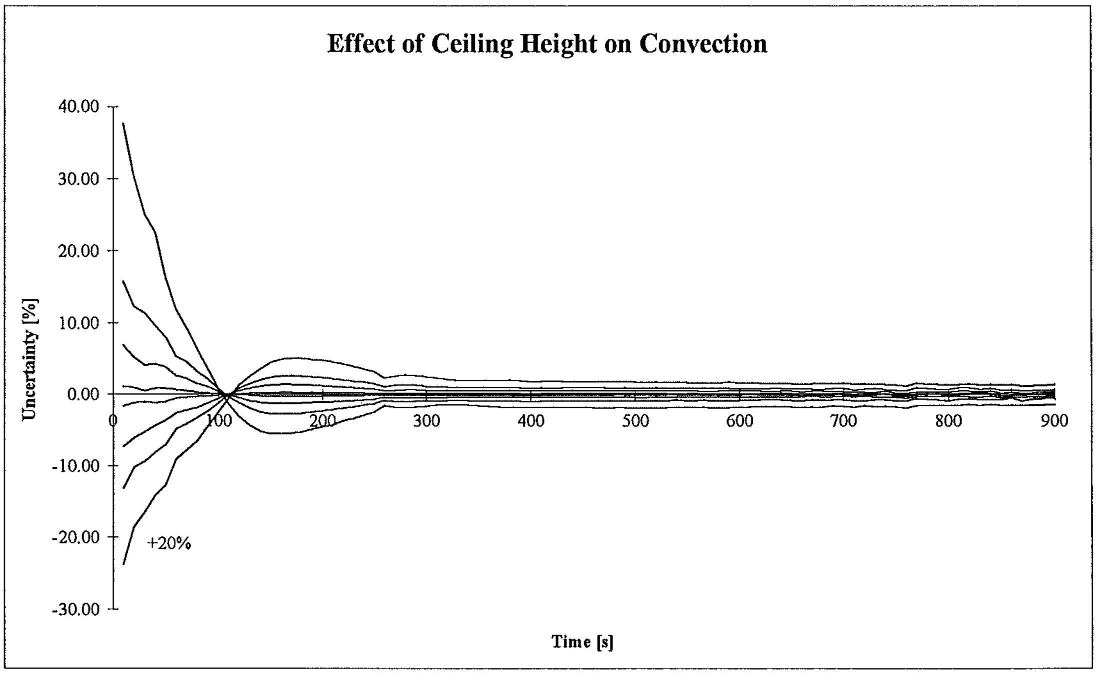
Effect of Ceiling Height on Mass Flow Out
Uncertainty [%]
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
+20%
0
100
200
300
400
500
600
700
800
900
Time [s]


Effect of Ceiling Height on Mass Flow In
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

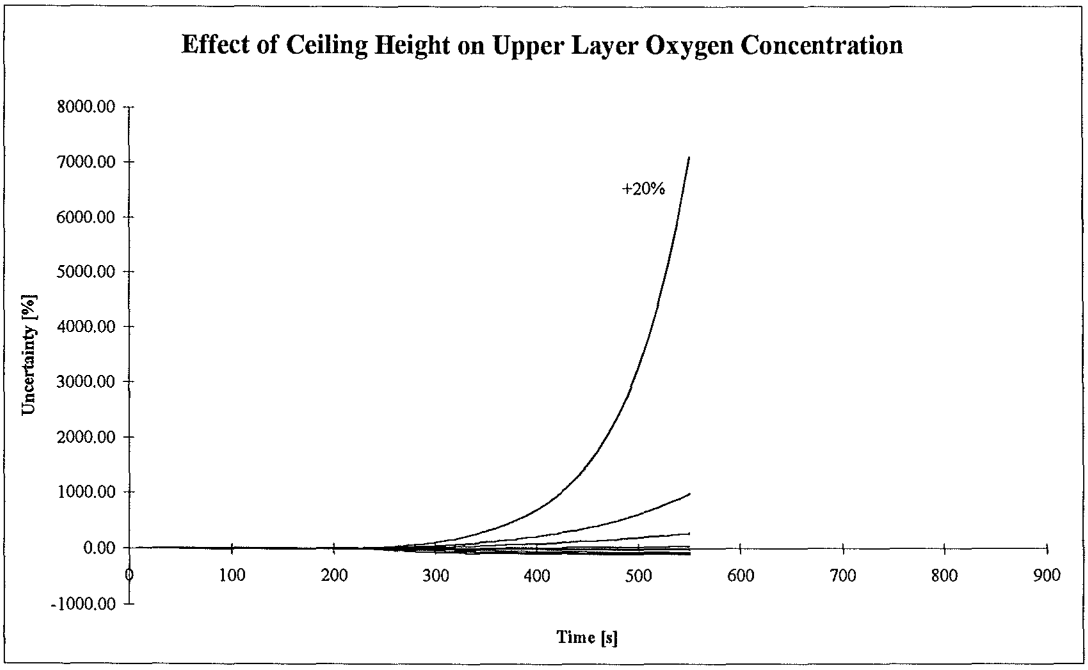

Effect of Ceiling Height on Vent Fire
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

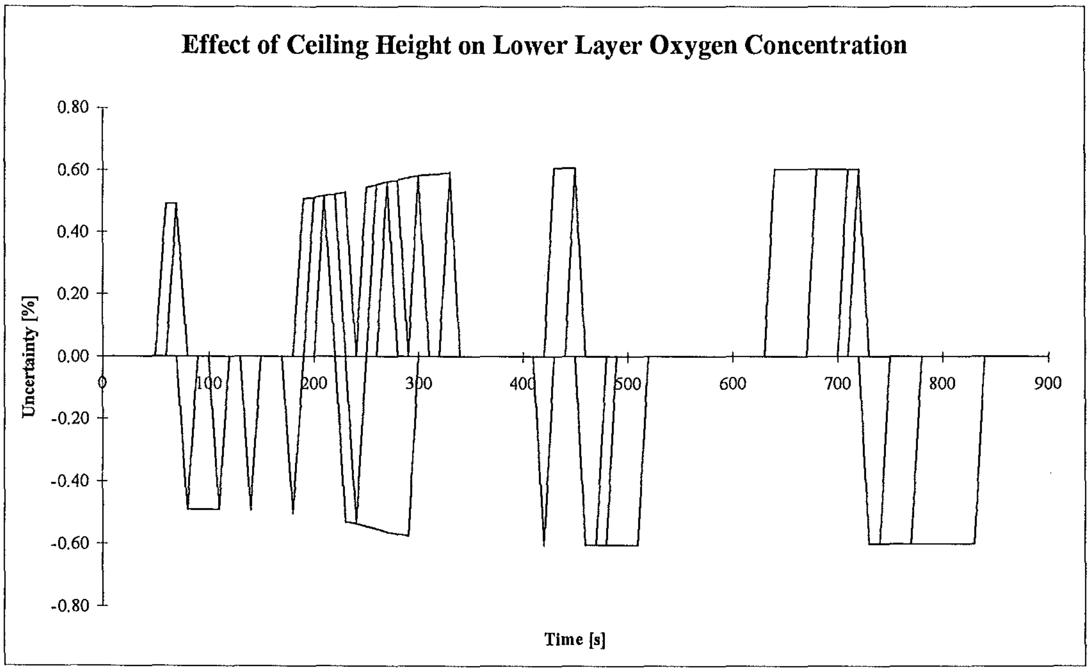


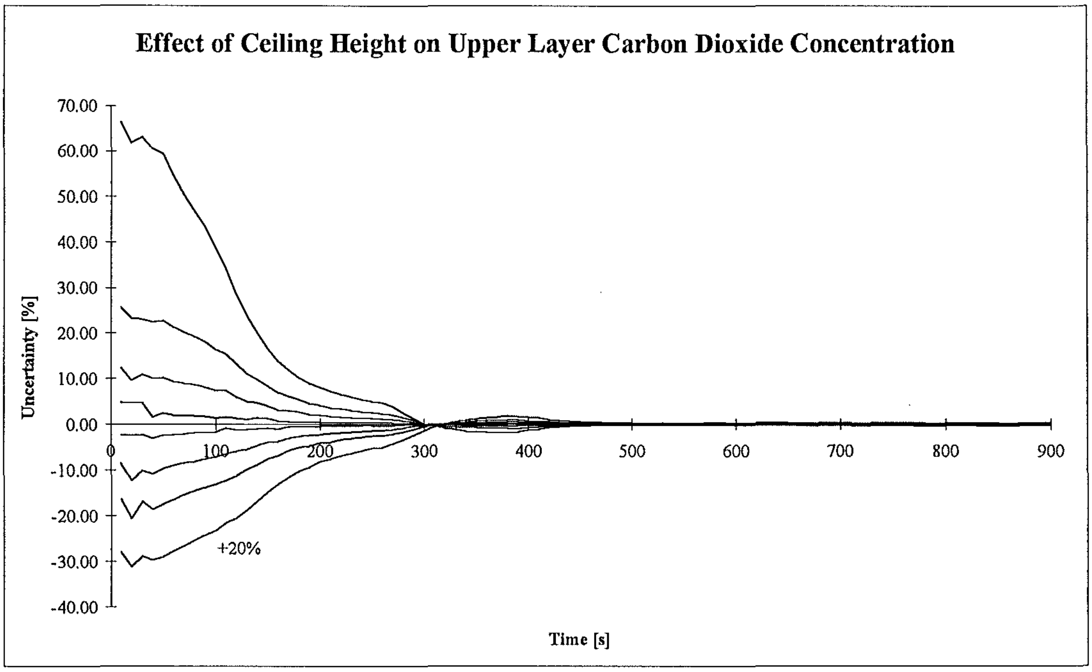
Effect of Ceiling Height on Radiation
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]



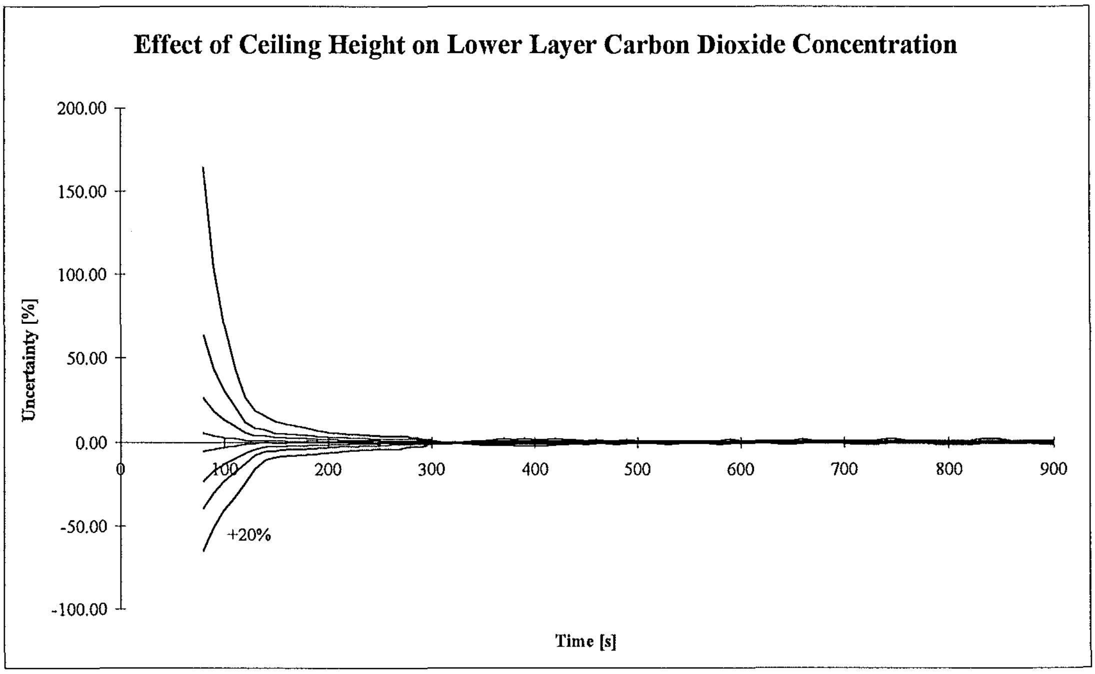
Effect of Ceiling Height on Convection
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Uncertainty [%]
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]


Effect of Ceiling Height on Upper Layer Oxygen Concentration
+20%
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
-1000.00
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]


Effect of Ceiling Height on Lower Layer Oxygen Concentration
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
0
100
200
300
400
500
600
700
800
900
Uncertainty [%]
Time [s]

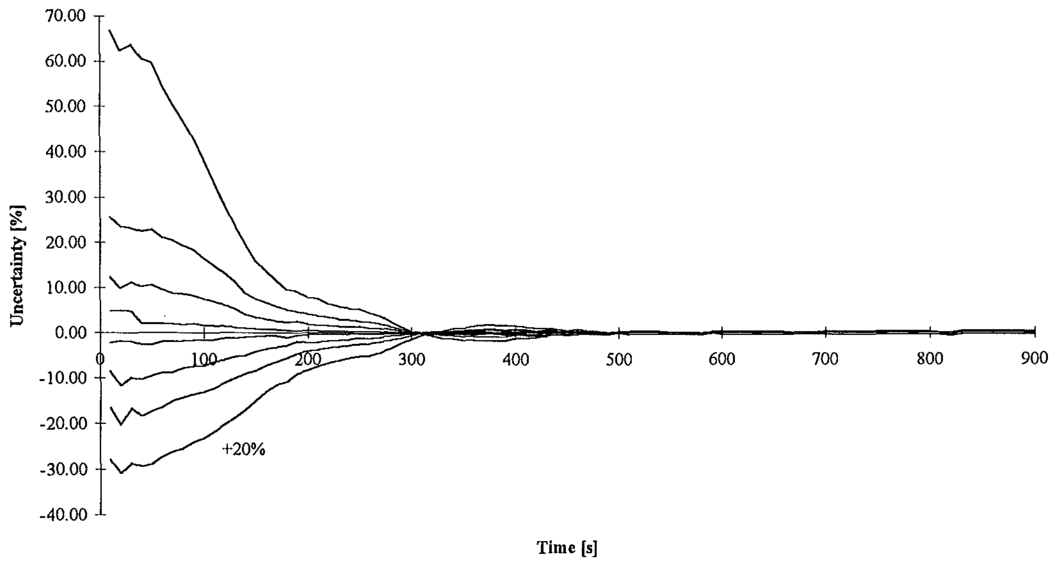


Effect of Ceiling Height on Upper Layer Carbon Dioxide Concentration
Uncertainty [%]
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

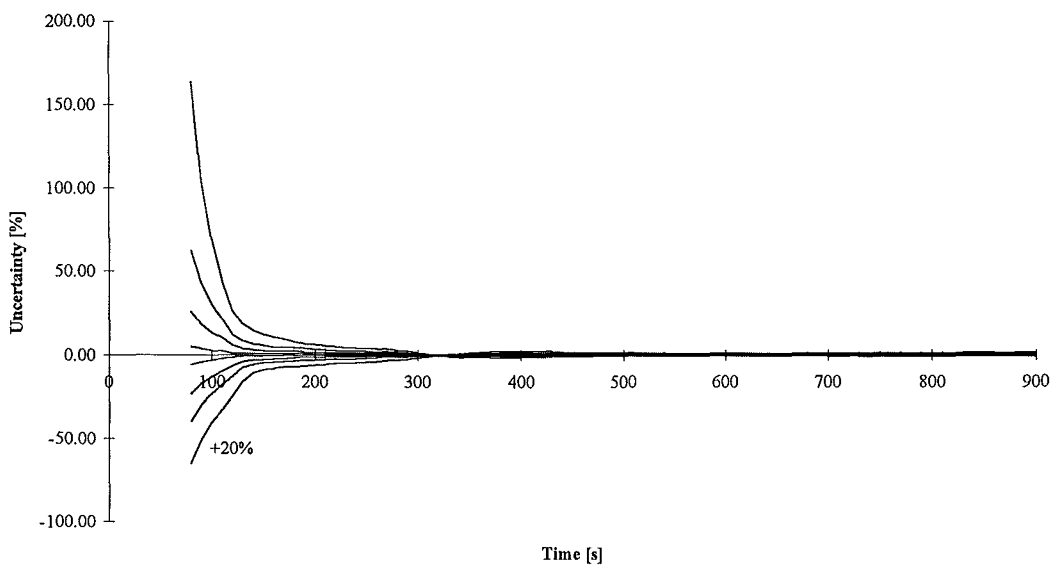


Effect of Ceiling Height on Lower Layer Carbon Dioxide Concentration
Uncertainty [%]
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
0
100
200
300
400
500
600
700
800
900
+20%
Time [s]

Effect of Ceiling Height on Upper Layer Carbon Monoxide Concentration



Effect of Ceiling Height on Lower Layer Carbon Monoxide Concentration



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